Opportunities to Improve the Irrigation Efficiency of Dairy Pasture Systems through Management of Water Resources and an Understanding of Plant Water Relations

By

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Statements and Declarations

Statement of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of the background information and duly acknowledged in this thesis, and to the best of my knowledge and believe no material previously published or written by another person except where due acknowledgement is made in the text of the thesis.

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Statement of ethical conduct

The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

Meisha-Marika Holloway-Phillips

Statement regarding published work contained in this thesis

The results of Chapter 2 have been published in a peer-reviewed international journal and Chapter 6 is currently in press. The publishers of these papers hold the copyright for the content, and access to the material should be sought from the respective journals.

Whilst the results are the same in both published and thesis forms, the text may vary slightly in both cases.

Chapter 2

Holloway-Phillips M, Brodribb TJ (2011) Minimum hydraulic safety leads to maximum water-use efficiency in a forage grass. *Plant, Cell and Environment* **34**, 302-313.

Chapter 6

Holloway-Phillips M, Brodribb TJ (2011) Contrasting hydraulic regulation in closely related forage grasses: Implications for plant water use. *Functional Plant Biology* **38**, 594-605.

Statement of co-authorship

Both papers listed above, were co-authored with Dr. Timothy J. Brodribb. His contribution in both cases involved assistance with the conceptualisation and technical implementation of the study, as well as editing of the manuscripts. As a proportion, T. J. Brodribb contributed 30% to the publication of the work undertaken as part of this thesis, and M. M. Holloway-Phillip, 70%.

We the undersigned agree with the above stated "proportion of work undertaken" for each of the above published peer-reviewed manuscripts contributing to this thesis:

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List of common abbreviations and symbols

Units:

ML	Mega litre
ml	millilitres
cm	centimetre
m	metre
h	hour
s	second
min	minute
°C	degrees Celsius
t	tonne
ha	hectare
MPa	Megapascal
KPa	Kilopascal

Soil nutrients:

P	Phosphorous
K	Potassium
S	Sulphur
N	Nitrogen

Species:

Perennial ryegrass	*Lolium perenne* L.
Annual ryegrass	*Lolium multiflorum* Lam.
Tall fescue	*Festuca arundinacea* Schreb. [syn. *Lolium arundinaceum* (Shreb.) Darbysh.]

Herbage production and nutritive value:

DM	dry matter
WSC	water-soluble carbohydrate
NDF	neutral detergent fibre
DOMD	digestibility of organic DM
DDM	digestible DM
CP	crude protein
ME	metabolisable energy

Water balance:

PET	potential evapotranspiration (FAO-56 method or pan evaporation)
ET	evapotranspiration (unit: mm)
WUE	water use efficiency (refers to both leaf and field level responses)
VPD	vapour pressure deficit (unit: KPa)
RWC	relative water content (unit: %)
VWC	volumetric water content (unit: %)
RAW	readily available water
Ψ_{soil}	soil water potential (unit: KPa)
DU	distribution uniformity (unit: %)
GMS	granular matrix sensors

Physiology:

YFEL	youngest fully expanded leaf
Ψ_{leaf}	leaf water potential; Subscript PD = predawn and MD = midday (unit: MPa)
gs	stomatal conductance (unit: mol $m^{-2}s^{-1}$)
E	transpiration (unit: gs^{-1} $gdwt^{-1}$)
A	assimilation (unit: µmol $m^{-2}s^{-1}$)
K_{leaf}	leaf hydraulic conductivity (leaf relaxation technique) (unit: mmol $m^{-2}s^{-1}$ MPa^{-1})
K_{plant}	whole plant hydraulic conductivity (defined as $K_{plant} = (\Psi_{PD} - \Psi_{MD})/E$)
OA	osmotic adjustment
TLP	turgor loss point
ABA	abscisic acid

Seasonal climate forecasting:

SOI	Southern Oscillation Index
ENSO	El Nino-Southern Oscillation
CDF	cumulative distribution function
ABARE	Australian Bureau of Agriculture and Resource Economics
ABS	Australian Bureau of Statistics
BOM	Bureau of Meteorology

Statistics:

s.e.m.	standard error of mean
r^2	refers to the adjusted coefficient of determination of linear models
R^2	refers to the pseudo-R square or estimated coefficient of determination for non-linear models

Terms and definitions

DEFICIT IRRIGATION:

Regulated deficit irrigation (RDI)

Where soil water budgeting or monitoring of plant physiological attributes directs the timing of irrigation events.

Conventional deficit irrigation (CDI)

Where the irrigation interval is maintained but only a proportion of evapotranspiration requirements are applied at each irrigation event.

WATER USE EFFICIENCY:

Leaf level – denoted as WUE_l and calculated as *A*/*gs*, where *A*=assimilation and *gs*=stomatal conductance (unit: µmol CO_2/mol H_20)

Field level – referred to generally as *irrigation efficiency* and expressed as various production indices (unit: t DM/ML):

Marginal irrigation water use index (MIWUI)

MIWUI = (irrigated yield-dryland yield)/irrigation water applied

Gross production water use index (GPWUI)

GPWUI = total production/total water applied (irrigation + rainfall)

Irrigation water use index (IWUI)

IWUI = total production/irrigation water applied

PRODUCTION

Dry matter consumed - that which is consumed by grazing cows, measured as the standing height of pasture before and after grazing with a calibrated rising plate meter

Dry matter yield - that which is grown and measured as cut herbage >5 cm from the soil surface

Dieback - leaf senescence progressing from the tip of the leaf blade

Forage - refers to both crop and pasture species

Abstract

This thesis investigates the capacity to improve irrigation efficiency in dairy pastures through the practice of deficit irrigation. In this practice, less water is applied than is needed to meet full losses from evapotranspiration (ET), thus creating a soil water deficit and exposing plants to mild water stress. Deficit irrigation has been successfully used in various crops to reduce irrigation demand with minimal penalty to yield. However constraining production of pasture growth under reduced water availability is the linear relationship between biomass and ET. Two options investigated in this thesis to reduce the risks to pasture production were the potential to improve, instantaneous water use efficiency through stomatal regulation of water use (A/gs; WUE_l) (leaf-level response), and irrigation efficiency (yield/irrigation applied) through increased rainfall capture (field-level response). Management options to mitigate the increased risks of practicing deficit irrigation associated with spatial and temporal variability of water requirements and climate uncertainty were also considered, including soil moisture monitoring to improve irrigation scheduling precision, climate forecasting to reduce uncertainty around irrigation requirements, and breeding opportunities for improved drought resistance.

Knowledge of how stomata regulate water use and the importance of maintaining hydraulic connection between leaves and the soil for growth and survival (leaf area maintenance) under soil water deficits, were used as the basis to investigate both the limitations and opportunities to augment WUE_l. *Lolium perenne* L. (perennial ryegrass) is the dominant pasture species grown in temperate dairy systems, and was the focus of this study. Perennial ryegrass was identified as being intrinsically drought-sensitive according to the leaf xylem, which was highly susceptible to water stress-induced declines in hydraulic conductivity. Furthermore, stomata provided no protection against hydraulic dysfunction, closing well after the point where hydraulic conductivity had declined by 50 %. Despite the lack of safety conferred by stomata, hydraulic dysfunction was neither detrimental to assimilation up to a point, nor restrictive to the recovery of hydraulic conductivity on rewatering. As a result diurnal soil water availability could be manipulated in order to achieve increases in WUE_l without affecting dry matter (DM) yield (g/plant).

A range of deficit irrigation strategies were tested to improve irrigation efficiency under field conditions. Increasing the cumulated potential evapotranspiration (PET) deficit from 20 mm

to 60 mm before irrigation was triggered, resulted in a 50 % saving in irrigation inputs over the experimental period with no significant effect on herbage DM yield (t DM/ha) or nutritive value. When the scheduling practice was further tested at the paddock scale with grazing cows, there was however a linear decline in DM production with irrigation inputs. However, under conditions where the distribution uniformity of irrigation application was low, the variability in DM yield was similar between well-watered and deficit irrigation treatments suggesting that there was no additional risk to yield from increasing the soil water deficit to a maximum threshold of 60 mm. Furthermore, gas exchange and leaf water potential measurements sampled across a range of soil water potentials in the field indicated that on average the increase in WUE_l between well-watered and deficit irrigated plants was 18.7 %, compared with a 53.5 % increase which had been achieved under glasshouse conditions. High variability in leaf water potential and hence WUE_l with soil water potential, demonstrated the difficulty in the field to maintain tight control on WUE_l. A comparison between irrigation scheduling methods showed that the use of granular matrix sensors improved irrigation scheduling precision resulting in a 0.24 t DM/ML increase in the response of pasture to irrigation inputs, with a water-saving of 20-33 % compared with where irrigation was scheduled according to a PET-based rainfall deficit.

Seasonal climate forecasts based on the Southern Oscillation Index 5-Phase system were used to optimise the choice of the irrigation scheduling practice for Elliott, on the north-west coast of Tasmania. Probability distributions of modelled irrigation requirements were constructed using historical climate data from 1901 to 2008, as well as yield distributions under 4 different deficit irrigation strategies using the biophysical model, DairyMod. The reliability of the forecast system to predict differences in irrigation requirements (mm/year) between the SOI Phases appeared poor with statistical differences between the cumulative distribution functions of irrigation requirement non-significant when the *P*-values were adjusted for multiplicity. This was consistent with the considerable overlap observed between 95 % confidence intervals. However in terms of user value, the forecast system maximised DM production over a fixed scheduling strategy when water was non-limiting, whilst reducing the water requirements by 8.5%. When the irrigation allocation was capped at 250 mm (50% reduction of maximum requirements), there was less differentiation of irrigation requirements between SOI Phase distributions, negating the need for pre-season information and limiting the opportunity to improve irrigation efficiency.

Breeding presents another potential avenue for improving the DM response to water inputs and was approached from the point of view of understanding differences in water transport characteristics between closely related forage grasses to assess the potential DM trade-offs associated with increased drought resistance. Cultivars of two common forage grass species were assessed with different drought performance ratings, including *Lolium multiflorum* Lam. and *Festuca arundinacea* Schreb. Species of the *Festuca-Lolium* complex were specifically chosen as their chromosomes share sufficient homology to pair and recombine providing much opportunity for the breeding of model genotypes. It was found that whilst vulnerability of xylem to hydraulic dysfunction (a measure of dehydration tolerance) was comparable, for *F. arundinacea* cultivars there was greater hydraulic risk associated with reduced stomatal sensitivity to leaf hydration. In contrast, *L. multiflorum* cultivars expressed a higher capacity for water transport, but more conservative stomatal regulation. Under acute soil drying, *F. arundinacea* was as a result more susceptible to leaf damage. However, under the sustained moderate drought conditions in this experiment, the two strategies were balanced in terms of water conservation and hydraulic utilisation, resulting in similar DM production.

This thesis uses an integrated approach to investigate the opportunities for improving the irrigation efficiency of dairy pasture systems. Leaf level assessment indicated that the forage grass species tested had the capacity to lose more water than required to maintain optimal DM production. However at the field level, regulating soil water availability through irrigation scheduling to restrict stomatal regulation of water use was difficult to achieve due to the large amplitude in soil water experienced in each of the irrigation treatments. Options for mitigating the risks associated with deficit irrigation, including the use of soil moisture monitoring and climate forecasting, were demonstrated as well as implications for the breeding of drought resistant grass species based on how the coordination between hydraulic capacity and water use regulation influences biomass production and water use efficiency. The results of this thesis provide important information to the management of pastures in water-limited environments, as well as illustrate the general need for management practices to be designed in context of the crop's physiology.

Chapter 1: Introduction

1.1 Research context: Background to water use in the Australian dairy industry

1.1.1 Importance of irrigation water – facts and figures

The Australian dairy industry comprises 8 dairying jurisdictions, which are represented in Figure 1.1. Tasmania, southern Victoria and the south coast of New South Wales are characterised by a temperate environment, receiving over 800 mm of rainfall annually. Within Tasmania, annual rainfall is variable – from less than 900 mm to over 1,200 mm across the north of the state. Under this relatively high rainfall, perennial ryegrass (*Lolium perenne* L.) forms an important component of the feedbase due to its high feed value, quick establishment and high biomass production (Oram & Lodge 2003; Wilkins & Humphreys 2003). However, under water-limited conditions and high temperatures, perennial ryegrass displays poor persistence and reduced herbage quality, which can result in feed shortages during dry summer conditions (Waller & Sale 2001). The research presented in this thesis focuses on perennial ryegrass in the important north-west Tasmanian dairying region.

Pasture-based dairy systems are considered the most profitable with pasture consumption a key driver of dairy business success (Armstrong *et al.* 2010; Chapman *et al.* 2008; Ho *et al.* 2007). However, to achieve maximal pasture yields, the industry relies heavily on irrigation water to overcome summer rainfall deficits, and on a national scale, this accounts for 19 % of the total water diverted for agricultural use (ABS 2006). In addition, the economic returns on irrigation water tend to be much lower for dairy, with the national gross production economic water use index for 2007-2008 estimated at $2,868/ML compared with $4,093/ML for fruit production and $6,901/ML for vegetable production (ABS 2010a). However, in the Murray-Darling Basin alone where the majority of dairy farming occurs, irrigated production is estimated to account for 80 % of gross value for the dairy region ($1172 M 2005-06) (ABS 2008).

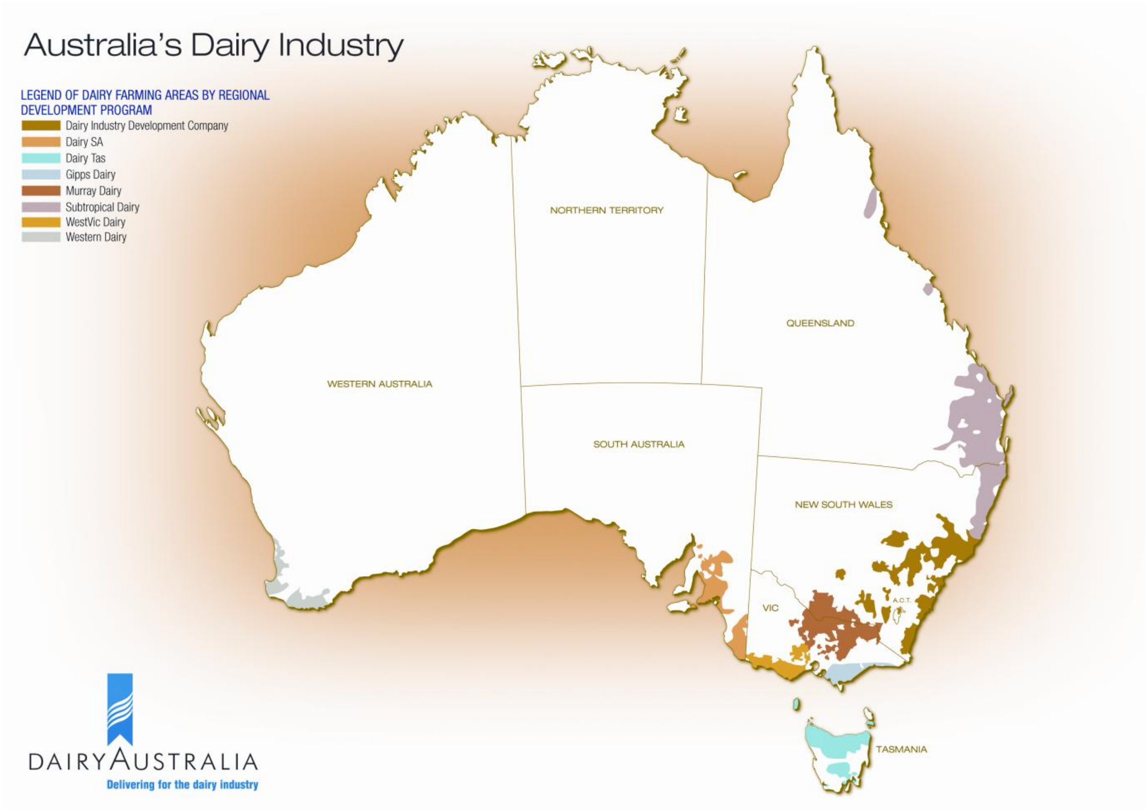

Figure 1.1 The 8 dairying regions that comprise the Australian dairy industry (Source: Dairy Australia)

In Tasmania, irrigated dairying makes up 23 % of the total irrigated land and uses 33 % of the State's water diverted for agricultural use (ABS 2006). Furthermore, 67 % of farmers are reliant on irrigation water to some extent, irrigating an average of 41% of their land (Watson 2006) at an average rate of 4.3 ML/ha (ABS 2006). This figure is likely to continue to increase with the 2009 Dairy Situation and Outlook survey reporting 40 % of respondents planning to increase the amount of land irrigated (DA 2009b). On the north-west coast modelled findings suggest irrigation can increase annual dryland production by an average of 44 % with industry targets of 10.2-16.7 t DM for rainfed pasture production and 22.5-25.1 t DM for irrigated production (Donaghy *et al.* 2008). Irrigation infrastructure upgrades and purchasing of water entitlements are considered of high priority for reducing climatic risk and expanding business, with irrigated farms generally running larger herds at a higher stocking rate (Watson 2006). The introduction of new irrigation and water management practices was the highest ranked innovative change made over the two years ending 2007-08 in the dairy industry (Liao & Martin 2009), despite the fact that one of the greatest concerns is continued irrigation availability, and hence returns on investment (DA 2009a).

1.1.2 Impact of limited water availability

Climate variability, particularly fluctuations in rainfall amount and distribution patterns, is a major constraint to production and profitability in agriculture (Nelson & Kokic 2004). Persistent below-average rainfall for significant parts of southern and eastern Australia since 1996 (BOM 2011), has caused widespread drought and subsequent reductions in river stores and inflows. In recent years this has resulted in significant reductions in water allocated to irrigation (Sanders *et al.* 2010) and subsequent increases in water prices (Mallawaarachchi & Foster 2009). In the period 2005-06 to 2007-08 alone, irrigated land use in the Murray-Darling Basin declined by 42 % (Sanders *et al.* 2010). High security water entitlements were at their lowest in the 2008-09 period with the Victorian Goulburn region recording declines to 33 % of allocations (Sanders *et al.* 2010).

The combination of ongoing drought and reduced milk prices in the 2006-07 period resulted in an estimated decline in farm cash income of around 61 % from the previous year (Hooper *et al.* 2008). Relatively high farm gate milk prices were able to buffer continued decreases in milk production in the 2007-08 period with the highest cash income recorded in more than 20 years (ABARE 2009). However the fall in prices for manufactured dairy products in 2008-09 once again exacerbated continued dry conditions in parts of southern Australia, although to a lesser degree than the 2006-07 period (ABARE 2009).

Potentially compounding market pressures, the projected future climate for Tasmania under current climate change scenarios predicts higher temperatures (1.6-2.9^{o}C under low and high emissions scenarios respectively) with little change in mean annual rainfall but with some changes in seasonality – in particular, a reduction in summer rainfall in the far north-west and increases in autumn and summer rainfall in the east of Tasmania (Holz *et al.* 2010). There is considerable inter-model variability indicating uncertainty, but general trends suggest a reduction in the proportion of time subject to meteorological drought in the south-east, north-east and south-west of Tasmania, and an increase in the central to north-west regions.

Increases in daily temperatures with corresponding increases in atmospheric carbon dioxide (CO_2) concentrations are likely to have a positive effect on annual pasture yields in most Tasmanian dairy regions, with irrigated pasture yield projected to increase by around 20-30 % by 2040 (Holz *et al.* 2010). Thereafter a decline to current pasture yields is predicted to occur due to increases in the number of days exceeding 28^{o}C. Importantly, improved water use efficiency (WUE) from increases in CO_2 concentrations suggests that water use is unlikely to change substantially despite higher yields, and furthermore, increases in water extractions are predicted to be less than the reduction in non-extracted water for most areas of Tasmania (CSIRO 2009).

Water use predictions for Tasmania contrasts with the Murray-Darling Basin which is projected to experience reductions in surface water availability of between 3-21 % (CSIRO 2008), placing Tasmania in a strategic position for continual growth and expansion of the dairy industry. The impact on producer income in the Murray-Darling Basin has been predicted to only reduce by 1 % on average by 2030, however this estimate assumes large changes to productivity through practice, and reallocation of water to higher value, more water-efficient crops (Goesch *et al.* 2009). As such, dairy activity as a percentage of land use is predicted to decrease by 2.5 % (third behind broadacre and rice crops), with a consequent reduction in water use by the industry. Whatever the case, preparedness for change is required to equip producers to make tactical decisions to reduce the risk associated with climatic uncertainty (Frontier-Economics 2010; George *et al.* 2007; Topp & Shafron 2006), with the general need to reduce water use and maximise returns in order to remain viable and environmentally sustainable.

1.1.3 Gaps in knowledge and skill as identified from the experience of drought: research opportunities

Since water availability has become a heightened issue there has been greater effort to collect water use data and conduct farm surveys on industry response and management practice under conditions of low water availability. This information has been useful in identifying opportunities to improve on-farm water use and where gaps in knowledge and skill currently exist. In the dairy industry, short-term responses tend to include reducing the irrigated area, buying in feed when the price of temporary water reaches a threshold and reducing herd feed demands, with longer term changes including upgrading irrigation infrastructure, changing crop mix and securing more water entitlements (Austen *et al.* 2002; Doyle & Johnson 2004; Mallawaarachchi & Foster 2009; Sanders *et al.* 2010). The adoption of any one strategy is likely to be dependent on the price and/or availability of water, to which the impact will vary according to differences in resource inventories and production systems of farms and the capacity to adjust to changes in the operating environment (Doyle & Johnson 2004).

The complexity in improving the efficiency of water use is reflected in the different measures used to benchmark improvement, namely the dry matter (DM) response of pasture to irrigation (hereby referred to as irrigation efficiency) or total water inputs (irrigation + rainfall) (t DM/ML), or the amount of milk (kg fat + protein) produced from pasture per ML of total water inputs. The advantage of the latter measure is that it reflects the integrated response of both pasture and husbandry management decisions, however as a result, it is also difficult to identify what part of management is inefficient. An economic analysis by Armstrong (2004) found that there was no direct association between milk/ML and profitability, or between milk production and operating profit, highlighting the fact that conversion of home-grown feed to milk requires optimal utilisation for improvement in irrigation efficiency to be realised (Armstrong *et al.* 2000), and further that infrastructure investments may be required in order to initially attain efficiency improvements.

In a study of 90 producers across the Murray-Darling Basin over four consecutive seasons (1994-95 to 1998-99), Linehan *et al.* (2004) noted the tendency for the irrigation application rates to remain the same between years despite differences in allocation constraints across the seasons. This suggests that producers opted to buy additional water or reduce the irrigated area before reducing the irrigation application rate. Furthermore there was a large range in application rates (4.1-13.2 ML/ha) and pasture consumed (2.4-17.7 t DM/ha) suggesting that irrigation efficiency was variable, and hence an opportunity for efficiency gains through improved irrigation scheduling decisions and grazing management.

Efforts to improve irrigation efficiency have been mainly focused on application efficiencies through changes to irrigation infrastructure and re-use systems (Mosley & Fleming 2009; Watson & Drysdale 2005; Wood *et al.* 2007; Wood & Finger 2006), alternative forage species with higher intrinsic WUE (Greenwood *et al.* 2008; Neal *et al.* 2010; Neal *et al.* 2009), and capacity building through greater extension programs and the development of on-farm irrigation tools (Chapman 2007). However, less emphasis has been given to irrigation scheduling strategies associated with the allocation of water across the season when availability is below crop water requirements. This is reflected in the fact that only 37 % of farmers currently use any form of objective measure to schedule irrigation events (ABS 2010b), and in the past have generally run out of water before the end of the season (Freeman 2007).

Irrigation scheduling provides a means to maximise the use of water inputs (rainfall and irrigation) through both the timing and amount of irrigation water applied, with the aim to avoid soil water levels reaching the stage where plant water stress causes reductions in WUE, and to minimise the losses of soil water below the root-zone or via runoff as a result of overwatering (Howell 1996; Jones 2004). In the high rainfall zone of southern Australia, which includes the majority of the dairy industry, the opportunity for rainfall to contribute to DM yield is often largely underestimated. This is due to the fact that when water is considered a non-limiting resource, irrigation has tended to be applied in excess of plant requirements to avoid the risk of a yield penalty, especially where the distribution uniformity of irrigation application is low (Fereres & Soriano 2007). Furthermore, the uncertainty in rainfall forecasts has tended to limit their incorporation into irrigation decisions (Austen *et al.* 2002). In practice this has meant the adoption of short-interval irrigation schedules, which increases the potential for rainfall post-irrigation to be lost through runoff or drainage beyond the root-zone. In this thesis, opportunity to increase irrigation efficiency through scheduling practices has been investigated by two main means; through manipulating soil water availability in order to improve the regulation of plant water use, and through increasing rainfall utilisation.

1.2 Research approach: Opportunities to improve irrigation efficiency

1.2.1 Constraints in pasture systems and trade-offs under water limited conditions

The opportunity to improve the DM response to water transpired at the leaf level relates to the non-linearity of the ratio between assimilation rate and stomatal conductance (Morison *et al.* 2008), such that under mild water deficits, transpiration is reduced more than assimilation (hereby referred to as leaf level WUE; denoted WUE_l). At the field level, regulation of plant water use has been achieved in a number of crops through adoption of irrigation practices such as deficit irrigation (DI) (Costa *et al.* 2007; Fereres & Soriano 2007; Morison *et al.* 2008). In the practice of DI, less water is applied than is needed to meet full losses from evapotranspiration (ET), thus creating a soil water deficit and exposing plants to mild water stress.

In crops where the reproductive structure is the harvested product, which includes most of the broadacre grain crops, vines and tree crops, DI is viable due to the saturating relationship demonstrated between harvest index and biomass production (Farre & Faci 2006; Kang *et al.* 2002). In these crops, DI is usually practiced by restricting water inputs to particular drought-sensitive developmental phases (referred to as regulated deficit irrigation; RDI). As perennial forage crops tend to lack defined phases, DI can be alternatively practiced by maintaining plants within certain soil water limits (another form of RDI), or through applying a proportion of crop water requirements at regular intervals (conventional deficit irrigation; CDI).

Whilst DI has been assessed extensively for turf grasses where aesthetics is the main objective (DaCosta & Huang 2006; Fu *et al.* 2007; Githinji *et al.* 2009), or utilised experimentally with line-source variable rate irrigation to assess the response of pasture plants to soil water deficits (Jensen *et al.* 2001; Smeal *et al.* 2005), as a commercial irrigation scheduling practice for dairy farmers where the objective is forage production, there are few guidelines on how to implement DI or the benefits and limitations of such a strategy, particularly in the Australian context. However the results of a local example, which recently investigated the use of CDI, were encouraging, with an increase in the DM response from 1.29 t DM/ML to 1.87 t DM/ML when 40 % of the ET requirements were applied (Rawnsley *et al.* 2009).

The main limitation of pasture grasses to achieving improved irrigation efficiency through DI, is the linear relationship between transpiration and biomass (Steduto *et al.* 2007), which suggests that water use must be maximised in order to gain maximum production. In this case, the greatest opportunity to save water is likely to be through reducing water lost via evaporation, runoff and deep drainage, which can be achieved through improved scheduling techniques that avoid overwatering, and by ensuring adequate ground cover to minimise evaporative water losses (Greenwood *et al.* 2009).

Furthermore, because of the trade-off between water conservation and utilisation there is a need to understand water use regulation in grass species and how this relates to morphological responses, in particular the resulting effect on DM yield. The effect of water stress on forage nutritive value is also an important consideration for irrigation management, as poor quality will result in reduced intake and therefore reduced pasture utilisation and conversion to milk production (Minson 1987). Current understanding of the morphological and physiological responses of forage grasses to water deficits will be discussed further in

Section 1.2.2, and management strategies to improve the precision of irrigation scheduling in Sections 1.2.3 and 1.2.4.

1.2.2 Forage selection

1.2.2.1 Effect of water stress on the growth and development of the grass plant and forage nutritive quality

The grass plant is comprised of the leaf blade (shortened to leaf throughout thesis) and sheath, tillers, and seminal and adventitious roots, which is illustrated in Figure 1.2. New leaves are initiated from the growing point (or apical meristem) located at the centre of the shoot which emerge according to the rate of leaf extension and the length of the sheath through which the emerging leaf grows. A tiller is a side-shoot that arises from a bud in the leaf axil of the parent shoot. Each tiller is a replica of the parent shoot, possessing its own apical meristem, leaves, nodes, internodes and adventitious roots. The original shoot gives rise to primary tillers which in turn produce secondary tillers and so on to form a plant composed of a number of tillers at different stages of growth. As tillers differ in their time of origin and size, they respond differently to environmental conditions, with young tillers generally sacrificed when resources are limited (Langer 1973). The number of leaves per tiller is relatively constant, maintained by the rates of leaf appearance and leaf senescence (Duru & Ducrocq 2000). For a vegetative perennial ryegrass tiller the number of leaves is generally 3, with the oldest leaf (the first to appear) undergoing senescence as the fourth leaf emerges (Fulkerson & Donaghy 2001).

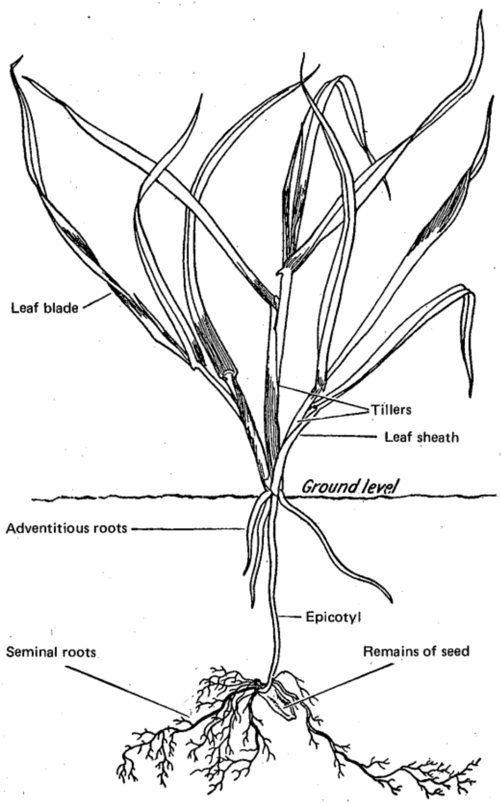

Figure 1.2 Young grass plant, with labelled leaf blade and sheath, tillers, seminal and adventitious roots (Source: Langer 1973).

During exposure to soil water deficits a number of morphological and physiological responses occur with the general aim to reduce the evaporative surface and hence the rate of water loss (Renard & Francois 1985), and maintain membrane stability and protect meristems for drought (Volaire & Lelievre 2001; Volaire *et al.* 1998). Stomatal closure is the first line of defence which prevents further short-term water losses, followed closely by leaf extension which is the most sensitive yield component to water deficits (Norris & Thomas 1982a; Thomas *et al.* 1999). Loss of turgor as leaf water potential (Ψ_{leaf}) declines causes leaf rolling in a number of grass species which helps to reduce the evaporative surface (Wilson 1975). Water stress can also cause an immediate reduction in root extension (King & Bush 1985), although in the long term, roots of plants infrequently irrigated tend to penetrate deeper in soil than roots of regularly irrigated plants (Jupp & Newman 1987), however total root mass does not always increase (Assuero *et al.* 2002).

Under continued soil drying, further decreases in the evaporative surface of plants occur through progressive senescence or dieback from leaf tips (Humphreys & Thomas 1993). Reliance on carbohydrate stores increases to support respiration processes, and eventually tiller death ensues (Thomas 1991; Volaire 1994; 1995). Browning off of pastures or leaf dieback is often observed in dryland production, resulting in reduced WUE. In the case of summer dormancy, rapid senescence is a programmed response that safeguards meristems during extreme dry conditions such as in Mediterranean environments to facilitate autumn regrowth (Nie & Norton 2009; Volaire *et al.* 2005).

The accumulation of water-soluble carbohydrates (WSC) has been associated with the capacity of plants to survive and regrow after drought (Volaire 1994), including the capacity of plants for compensatory growth, where the rate of leaf elongation exceeds that of plants not subjected to water stress (Corleto & Laude 1974; Horst & Nelson 1979). The accumulation of WSC also contributes to a decrease in osmotic potential (Thomas 1991). Osmotic adjustment (OA) has been associated with the maintenance of turgor and related metabolic processes (Hsiao *et al.* 1976; Morgan 1983), however this has not led to continued growth in all cases (Thomas & Evans 1991).

The nutritive value of pasture is a key determinant of feed intake by ruminants and energy conversion for milk production (Minson 1987). Changes in herbage quality can be partly due to changes in botanical composition as a result of the differential sensitivity of species to water stress. For example, ryegrass tends to out-compete white clover under water stress due to a larger root system and more efficient control of transpirational losses (Lucero *et al.* 1999). In terms of the direct effects of water stress on herbage quality attributes, rate of senescence and lignification of leaves and sheaths tend to increase, and subsequently the fibre content of the herbage. Increased fibre reduces the amount of herbage that can be ingested and therefore the energy obtained (Casler & Vogel 1999). One advantage of reduced growth rates under water stress is the increased concentration of leaf nitrogen (N), and subsequently crude protein (CP), which is an important source of energy. Jensen *et al*. (2003) indicated that the nutritive value of cocksfoot (*Dactylis glomerata* L.) and perennial ryegrass could be increased under water stress, observing near linear increases in CP with decreasing irrigation inputs without the obvious increase in fibre content.

The implications for the practice of DI is that due to the sensitivity of leaf growth to water deficits, the soil moisture deficit may need only be minimal before DM yield is reduced, but that quality may be less affected. The DM risks and nutritive value effects associated with increasing the soil water deficit are examined in Chapter 3. Where DM declines cannot be avoided, ensuring irrigation efficiency is not reduced due to leaf senescence or tiller death, and/or through an inability to recover on rewatering, is likely to be of greater relevance for establishing a water stress minimum for irrigation scheduling. With this in mind, selection of drought resistant species and cultivars may be a useful strategy to ensure leaf area maintenance and hence maximum DM returns when water inputs are minimal, which is discussed further below.

1.2.2.2 Water use regulation and associated traits

Much research has been undertaken to identify plant traits that confer advantage under limited water availability. In pasture grasses, drought performance can be distinguished as two major responses which reflect adaptive advantage to different patterns of summer soil moisture deficits. The first is *drought resistance* strategies which aim to maintain the existing aerial biomass, and are therefore highly suited to temperate environments where rainfall is more reliable. The second is *drought escape* which is achieved through summer dormancy, where rapid senescence of aerial biomass occurs endogenously in response to vernalisation and long days, but at the expense of dry-matter production. Drought escape is traditionally associated with annual species which complete their life cycles before water stress occurs, surviving the dry period as dormant seed. However, whereas the seed embryo is a whole plant, dormant buds in the case of perennial grass consists of a shoot only. Thus, summer dormancy has been shown to be adaptive in Mediterranean environments in which prolonged soil drying occurs, through protection of shoot meristems for long-term plant persistence (Nie & Norton 2009). McWilliam & Kramer (1968) and Volaire and Norton (2006) have used a similar categorisation for the case of dormancy.

The current thesis specifically investigates the capacity of cool-season forage grasses to maintain aerial biomass production under limited irrigation water and therefore the following discussion focuses on water responses pertaining to drought resistance strategies. Drought resistance is often assessed as the ability to maintain green leaf area or continued leaf extension (Carrow 1996; Humphreys *et al.* 1997; Humphreys & Thomas 1993; Richardson *et al.* 2008; Wang & Bughrara 2008; Zhou *et al.* 2009), or to use the least absolute amount of water and/or continue to transpire for the longest period (Zhao *et al.* 1994; Zhou *et al.* 2009), or to maintain leaf hydration (Volaire & Thomas 1995), and/or recover on rewatering (Norris & Thomas 1982a). These observations have been associated with traits such as low maximal stomatal conductance (Thomas 1986; Wilson 1975), a large root system (Garwood & Sinclair

1979; Huang *et al.* 1997; Qian & Fry 1997; Qian *et al.* 1997), and osmotic adjustment (DaCosta & Huang 2006; Qian & Fry 1997; Thomas & Evans 1989; 1991).

High WUE has also been selected for directly under the assumption that water conservation will confer drought resistance (Ebdon & Kopp 2004; Jensen *et al.* 2002; Johnson *et al.* 2003; Johnson *et al.* 1990; 2003). However, species and cultivars considered drought resistant or displaying high WUE are not in all cases the most productive under both well-watered and water deficit conditions. For example, the large root system of *Festuca arundinacea* Schreb. and its ability to extract water deep in the soil has been suggested to confer a DM advantage over its close relative *Lolium perenne* L. under water limited conditions (Durand *et al.* 2007; Garwood & Sinclair 1979; Nie *et al.* 2008). However, under well-watered conditions, *L. perenne* displays higher growth rates (Norris & Thomas 1982a; Thomas *et al.* 2003).

Inconsistencies in the adaptive value of water use traits are likely to reflect the different strategies associated with drought resistance, namely tolerance and avoidance strategies (Levitt 1972), which are suggested to carry costs and benefits optimised to a given environmental scenario (Tardieu 2005). According to the definition provided by Levitt (1972) and similarly Turner (1986), drought resistance is a general term used to describe a plants ability to survive an unfavourable environmental condition, in this case soil water deficits leading to plant water stress (reduction in plant water balance).

Strategies associated with drought resistance include *dehydration avoidance* and *dehydration tolerance*. Dehydration avoidance can be achieved through responses that either increase the capacity of the plant to continue to transpire water (a water utilisation strategy that tends to result in the maintenance of leaf growth), or responses that reduce water loss (a water conservation strategy that tends to limit carbon capture and therefore also growth). In terms of water balance, dehydration avoidance tries to minimise the reduction in plant water status, as maintenance of the existing aerial biomass tends to be limited as the water balance decreases. This compares to plants with enhanced dehydration tolerance, where there is greater capacity to recover the existing aerial biomass as plant water status declines. Importantly, dehydration avoidance and tolerance are not mutually exclusive mechanisms (Chaves *et al.* 2003), and maintenance of leaf growth doesn't result under all strategies.

To conceptualise the carbon trade-offs associated with the different strategies, the function and regulation of the water transport system are investigated on account of the shared stomatal pathway for water and CO_2 exchange in the leaf. By this premise, coordination between water transport function and mode of water use regulation exists to optimise the structural investment of the delivery system for a given environment (Sperry *et al.* 2002). The basis of this understanding is further discussed below.

The ability to maintain photosynthesis is dependent on a continuous replacement of transpired water, which is exchanged at a rate proportional to the xylem's capacity to transport water (Brodribb 2009). This physical process is supported by empirical observations showing xylem hydraulic conductivity is positively correlated with stomatal conductance, transpiration and photosynthetic capacity (Brodribb & Feild 2000; Hubbard *et al.* 2001; Meinzer 2002). Under drying soils however, hydraulic transport is susceptible to dysfunction with the generation of large tensions in the xylem as Ψ_{leaf} declines (Tyree & Sperry 1989). When this occurs, hydraulic conductance rapidly declines, compromising the capacity of the plant to transpire, which leads to eventual plant death by dehydration (Sperry 2000; Sperry *et al.* 2002).

Increased investment in the construction of xylem tissue can decrease the Ψ_{leaf} at which the hydraulic pathway is subject to dysfunction, which is typically assessed as the tension required to cause a 50% decline in hydraulic conductance (Blackman *et al.* 2009; Brodribb & Cochard 2009); hereby referred to as xylem vulnerability, denoted *P50*. Stomatal regulation can also provide hydraulic safety by reducing the rate at which Ψ_{leaf} declines (Sperry *et al.* 2002). Quantification of hydraulic safety usually involves measuring the difference between the Ψ_{leaf} at 95 % stomatal closure and *P50* (Brodribb & Holbrook 2004; Sack & Holbrook 2006). In terms of drought resistance, *P50* therefore sets a functional limit on dehydration tolerance, the costs of which may be moderated according to maximum hydraulic conductivity (K_{max}) through its link with assimilation, and stomatal regulation as a result of how close stomatal closure is to the point where growth is non-recoverable in order to maximise carbon gain. Thus, carbon/water trade-offs can be viewed at both the process level of gas exchange to the whole-plant level of function and form.

The significance of hydraulic efficiency and vulnerability to water use and DM yield in a forage grass is investigated for the first time in Chapter 1. There has been some research in rice (Stiller *et al.* 2003) and sugarcane (Neufeld *et al.* 1992), but in general, the comparative analysis of hydraulic efficiency and vulnerability in crop plants remains scant (Sperry *et al.* 2003). In Chapter 6 the link between water transport traits and drought resistance is further explored through examination of 2 species – *Lolium multiflorum* Lam. and *Festuca* *arundinacea* Schreb. (each consisting of 2 cultivars), with varying degrees of drought sensitivity.

The relevance of crop selection to the practice of DI relates to both the DM returns when water is limited, and the minimum soil water irrigation trigger before plant recovery is delayed or plant death occurs. In practical terms, this refers to balancing short-term water stress, which is determined by the irrigation application rate, and end-of-season stress eventuating where the irrigation allocation has run out before the season has ended. This balance is likely to change according to temporal and spatial variability in water requirements at the field level and inter-seasonally and therefore represents a risk in practising DI. In combination with forage selection, two other management strategies that may help mitigate these risks include climate forecasting and soil moisture monitoring, which are discussed in more detail in sections 1.2.3 and 1.2.4.

1.2.3 Climate forecasting

Optimisation algorithms are often applied to solving within season allocation problems in order to maximise production or profitability according to current water availability and short-term weather forecasts (e.g. Brown *et al.* 2010; Gowing & Ejieji 2001; Humphreys *et al.* 2008). However, whilst these types of models have shown potential in research applications at both the field and catchment level of management, fewer models have been developed commercially, most probably because they are complicated and require specific training and computer skills. Altering the application amount and/or scheduling interval at the beginning of the season to reflect the irrigation allocation may be a simple way to tailor the irrigation practice, which is conceptually easier to understand and therefore integrate within the management suite. To do this, prior information on whether the irrigation allocation meets the seasonal requirements is required in order to determine the scheduling practice that maximises production.

Rainfall variability is a key factor in the availability of irrigation allocations through catchment inflows, and seasonal irrigation requirements based on the prevailing rainfall deficit. Long-range seasonal climate forecasts are currently available for rainfall through the Bureau of Meteorology (Australia), which are useful for indicating whether irrigation will be below or above average requirements according to whether it’s a wet or dry year. However more specific knowledge of seasonal irrigation requirements, and therefore the scheduling approach, is needed for forecast utility in irrigated production systems. In the sugarcane industry this approach has been achieved by combining seasonal climate forecasts with simulation modelling of irrigation requirements to predict the likelihood of meeting the nominal crop water requirements in the upcoming season (Everingham *et al.* 2008), and similarly in the wheat (Hansen *et al.* 2004) and peanut industries (Meinke & Hammer 1997) to forecast rainfed production in Australia. Combining the capacity to simulate both irrigation needs and the resulting DM potential in pasture systems would allow for further tactical decisions to be made where the feed demand is not met, such as adjusting stocking or selling policies and buying in additional feed and temporary water. The potential to use climate forecast systems to optimise the choice of the irrigation scheduling practice as a means to improve irrigation efficiency and DM yield outcomes is examined in Chapter 5.

1.2.4 Soil moisture monitoring

Replacing crop ET according to a soil water balance, is a commonly used scheduling method as it requires little infrastructure and therefore maintenance and expense. However the water balance approach does not consider spatial or temporal variability in water use at the paddock level and is therefore subject to cumulative errors (Jones 2004). The use of direct measures of soil water availability through the use of soil moisture sensors may be an additional tool to aid DI scheduling (Greenwood *et al.* 2010; Pardossi *et al.* 2009; Shock & Wang 2011). Consideration of spatial and temporal differences in water use demand should improve irrigation efficiency through reducing the amplitude change in soil moisture and hence the occurrence of over-watering and subsequent water losses via deep drainage, or severe water stress from excessive soil moisture deficits. Soil moisture sensors also provide the opportunity to combine precision irrigation techniques where water is applied variably across a given area according to demand (Krum *et al.* 2010; Sadler *et al.* 2002). However adequate surveying of spatial variability in soil hydraulic characteristics is required, as well as an understanding of the impact of soil variation on yield, for soil moisture sensors to provide greater accuracy than an ET-based estimate of water use (McCready *et al.* 2009). Furthermore, the cost and performance of sensors varies greatly, and requires correct installation, calibration and placement within the soil profile for readings to be reliable (Greenwood *et al.* 2010). Therefore in some situations, investment in soil moisture monitoring may not be justified (DeJonge *et al.* 2007). The use of granular matrix sensors to improve the regulation of plant water use is investigated in Chapter 4.

1.3 Aims of the thesis

The general aim of this thesis was to investigate the opportunity of DI to improve irrigation efficiency in temperate pasture systems. The north-west dairying region of Tasmania was the focus of this research as there is substantial in-season rainfall that is currently being underutilised and limited knowledge of how to allocate water over the season in order to maximise production when irrigation availability is below crop water requirements. This thesis demonstrates how an understanding of plant-water relations can be used to improve the precision in meeting crop water demand both spatially and temporally, and hence the DM returns on water applied. This is approached through 5 specific research aims:

1. To investigate the capacity to improve leaf level WUE through an understanding of how hydraulic conductivity, xylem vulnerability and patterns of diurnal gas exchange influence DM yield and WUE (Chapter 2);

2. To quantify the production risks or yield trade-off associated with increasing the soil water deficit in the field in order to improve the potential for rainfall capture, and hence irrigation efficiency (Chapter 3);

3. To investigate whether granular matrix sensors improve scheduling precision in terms of regulation of plant water use, through considering spatial and temporal variability in water demand (Chapter 4);

4. To assess the potential use of the Southern-Oscillation Index 5-Phase forecast system, to improve knowledge of irrigation requirements compared with best-bet climatology, in order to optimise the choice of the irrigation scheduling practice as a means to improve irrigation efficiency and DM yield outcomes (Chapter 5); and

5. To investigate how characteristics of the water transport system differ between closely related grass species with different drought performance ratings, and how this is expressed in terms of a DM yield advantage under well-watered and water-deficit conditions (Chapter 6).

The experimental Chapters are presented in order of the 5 research aims above (Chapters 2-6), with synthesis of the study’s major findings and opportunities for future research presented in Chapter 7.

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Chapter 3: Investigating the dry matter trade-off in practising deficit irrigation to improve the irrigation response of perennial ryegrass

3.1 Introduction

Pasture-based systems are considered the most profitable solution to meeting the feed requirements of dairy cows in Australia (Armstrong *et al.* 2010; Chapman *et al.* 2008; Ho *et al.* 2007). However, to achieve maximal yields of pasture, the industry relies heavily on irrigation water to overcome summer rainfall deficits, and on a national scale, this accounts for 19 % of the total water diverted for agricultural use (ABS 2006). In addition, the economic returns on irrigation water tend to be much lower in dairy systems, with the Tasmanian gross production economic water use index for 2007-2008 estimated at \$2,546/ML compared with \$10,305/ML for fruit production and \$4,806/ML for vegetable production (ABS 2010a). With climate change and population growth predicted to exacerbate current water shortages (Rosenzweig *et al.* 2004), the Australian dairy industry is under pressure to improve water use efficiencies (WUE) in irrigated production systems, whilst still continuing to expand and develop for future demand and economic viability (Khan *et al.* 2010a).

The application of water below plant evapotranspiration (ET) requirements is termed 'deficit irrigation', and has been successfully used in various crops to increase WUE with minimal yield penalty (Fereres & Soriano 2007; Geerts & Raes 2009). In crops where the reproductive structure is the harvested product, which includes most of the broadacre grain crops, vines and tree crops, deficit irrigation is viable due to the saturating relationship demonstrated between harvest index (HI) and biomass production (Farre & Faci 2006; Kang *et al.* 2002). Specifically, growth tends to be more sensitive than photosynthesis to mild water deficits (Hsiao *et al.* 2007), resulting in reduced vegetative vigour for improved light penetration within the canopy for fruit ripening and partitioning of carbohydrates to reproductive organs (Chaves *et al.* 2007; Inman-Bamber *et al.* 2008; Zhang *et al.* 2008).

At the leaf level, increases in WUE occur under mild water deficits as stomatal aperture is reduced more than assimilation rate owing to the non-linearity of the ratio between assimilation rate and stomatal conductance (Morison *et al.* 2008). The potential of perennial ryegrass to increase WUE without negatively impacting biomass production was demonstrated in Chapter 2, where it was found that rapid recovery from water-stress induced declines in hydraulic conductance and non-linearity in the relationship between assimilation and hydraulic conductance enabled a substantial augmentation of DM yield per unit of water added, under restricted soil water deficits.

In general however, for non-reproductive herbaceous crops it is more difficult to reduce water inputs without a yield penalty as biomass production is tightly coupled to transpiration (Steduto *et al.* 2007). Thus in drier environments biomass will always be constrained as carbon acquisition is at the expense of water loss (Dudley 1996). The lack of specific developmental phases also eliminates the strategy of withholding irrigation at drought-tolerant stages. However, maintenance of crop water status within prescribed plant functional limits may be possible through the practice of regulated deficit irrigation (RDI), whereby soil water budgeting or monitoring of plant physiological attributes directs the timing of irrigation events (Jones 2004). In grass plants, the opportunity to practice RDI is largely dependent on the sensitivity of leaf growth to water deficits (Kelly *et al.* 2005; Merot *et al.* 2008; Milroy & Goyne 1995; Wang & Bughrara 2008), or where reductions in leaf extension cannot be avoided, the dehydration tolerance of foliage to prevent reductions in water productivity due to leaf senescence and tiller death (Humphreys & Thomas 1993), as well as drought-induced delays in regrowth (Hu *et al.* 2010; Lawn & Likoswe 2008) or tiller survivability (Volaire & Thomas 1995) following rain or irrigation. A recent study by Neal *et al*. (2010) illustrates the importance of the drought minimum on WUE, with larger declines in yield than in water use observed under a deficit irrigation scheme, reflecting the interaction between irrigation timing and drought sensitivity.

In Mediterranean environments, defined by terminal droughts and high temperatures, supplemental irrigation is one method that has been adapted to stabilise the yield in wheat (Oweis *et al.* 1998). In this instance, there is an opportunity to value-add to summer rainfall received by irrigating to stabilise yields (i.e. WUE is greater under a supplemental irrigation scheme than under dryland). In temperate environments, where summer rainfall tends to be more reliable, ensuring that the rainfall contribution is maximised through appropriate scheduling of irrigation becomes imperative. In this regard, water savings are met through greater rainfall utilisation which is quantified by an increase in irrigation efficiency.

The potential to increase irrigation efficiency in a temperate pasture system was recently investigated using a conventional deficit irrigation (CDI) approach where the irrigation interval was maintained but only a proportion of ET requirements were applied at each irrigation event. In this system, soil water depletion developed slowly, increasing the probability of capturing rainfall in the root-zone over time and allowing time for plants to adapt. It was found that by applying 40 % of the ET requirements, the marginal irrigation water use index [(irrigated yield – dryland yield)/irrigation water applied] was increased from 1.29 t DM/ML to 1.87 t DM/ML, presumably through reducing the potential for over-watering (Rawnsley *et al.* 2009). Whilst this strategy will always ensure an irrigation saving, the WUE achieved will be highly dependent on the seasonal conditions (evaporative demand, stored soil water and rainfall distribution), in regards to how quickly the critical soil water deficit is met and therefore the maximum stress incurred by the crop - i.e. the production risks are likely to be much higher in seasonally variable rainfall areas, especially with a concomitant high evaporative demand, and where a set irrigation scheduling practice is applied (Ganji *et al.* 2006; Sepaskhah & Akbari 2005).

The alternative strategy proposed in the current study is a regulated deficit irrigation approach, with the aim to isolate the seasonal effects on yield potential by controlling the maximum plant stress over an irrigation period. This is achieved through rewatering at 3 set cumulated potential evapotranspiration (PET) trigger points and refill points. By refilling to below field capacity, the soil profile is maintained within a tighter soil moisture range to control water stress, and provides space within the profile for rainfall capture. The differences in the two irrigation strategies are illustrated conceptually in Figure 3.1.

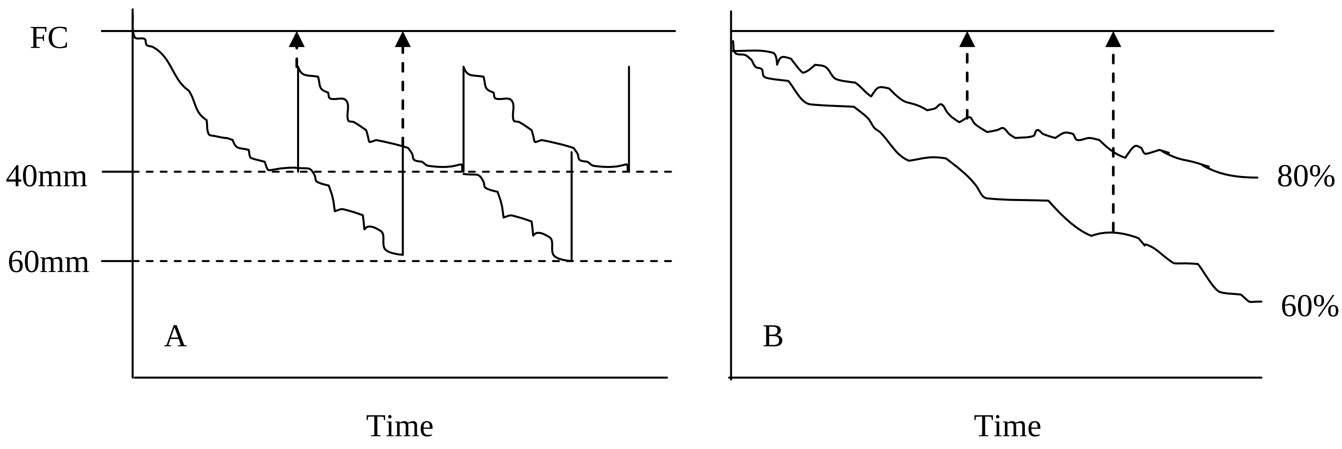


Figure 3.1 Conceptual diagram of the two deficit irrigation strategies – regulated deficit irrigation (RDI; A) and conventional deficit irrigation (CDI; B). The example of a 40 mm and a 60 mm soil water deficit threshold with watering to below field capacity demonstrates how the soil water deficit is regulated for the RDI strategy. This compares with the CDI strategy where without rainfall inputs the rate of soil drying is dependent on the proportion of water requirements applied, with in this case, the 60 % application rate drying at a steeper rate than the 80 % application rate. The arrows indicate the available space within the soil profile to capture rainfall.

The aim of the current study was therefore to quantify the production risks or yield trade-off associated with increasing the soil water deficit in order to improve the potential for rainfall capture, and hence irrigation efficiency. Furthermore, whilst the potential to increase WUE has been demonstrated under glasshouse conditions from a leaf-level physiological understanding, it us unknown whether this can be achieved through deficit irrigation management at the canopy level. Dry matter production was assessed, along with key drivers of production including plant energy levels, tiller density and growth rates, to identify yield limiting factors under reduced water availability. Herbage nutritive value is a key determinant of feed intake by ruminants and energy conversion for milk production (Minson 1987). Therefore in addition to yield attributes, the effect of deficit irrigation on herbage nutritive value was also tested through the potential effects of water stress on changes in botanical composition, and fibre and N content of herbage.

3.2 Materials and methods

3.2.1 Site and soil description

An experiment was conducted at the Tasmanian Institute of Agricultural Research Dairy Facility on the north-west of Tasmania, Australia (41.08°S, 145.77'E; elevation 155.0m) between December 2008 and June 2009. In this region, the irrigation season normally begins in November however it was not possible to begin irrigation treatments until January. Prior to commencement however, plots were maintained at field capacity by watering every 2-3 days, and confirmed by Watermark sensors (-10 KPa taken as field capacity) placed at a depth of 0.3 m in each plot.

Weather data were collected from the Australian Bureau of Meteorology weather station on the site, and Table 3.1 presents total rainfall, mean daily evaporation measured with a Class A pan, and mean maximum and minimum daily temperatures for each month of the experimental period. The climate for this region is considered temperate-maritime. The rainfall over the experimental period (January-April) was similar to the long-term average (1960-2009) rainfall of 260 mm for the same period.

Table 3.1 Total rainfall (mm), class A pan evaporation (mm/day) and temperature (minimum and maximum, ^{o}C) for each month of the experimental period (January to June 2009).

Month	Total rainfall	Evaporation	Temperature	
			Max.	Min.
January[A]	17.8	4.37	22.9	11.1
February	13.4	3.6	21.0	11.2
March	80.8	2.6	18.8	10.4
April	115.4	1.57	15.7	8.4
May	96.1	1.02	14.0	6.9
June[B]	65.8	0.66	11.9	5.6
TOTAL	389.3	362.5		

[A]Calculation period for the month of January begins on the 12th.

[B]Calculation period for the month of June end on the 25th.

The experimental site was an established perennial ryegrass (*Lolium perenne* L.) dominant pasture, on deep clay loam Ferrosol soil (Red Mesotrophic Haplic Ferrosol; Isbell 1996). Agritone® (active ingredient MCPA, present as dimethylamine salt, 750 g/L) was sprayed at a rate of 1.5 L/ha in October 2008 to remove broadleaf weeds, and the site was oversown with the perennial ryegrass cultivar ‘Impact’ to ensure adequate plant density (minimum of 150 plant m^{-2}; Fulkerson *et al.* 2003). Analysis of the soil before the study commenced indicated mineral concentrations of 18.2 mg phosphorus (P)/kg (Olsen P test), 242 mg potassium (K)/kg (Colwell K test), and 9.9 mg sulphur (S)/kg (potassium chloride extracted S), as well as a pH (H_2O) 6.2, and electrical conductivity 0.10 dS/m. Following soil test results, the experimental site was fertilised with triple superphosphate (21 % P, 1 % S), muriate of potash (50 % K) and single superphosphate (9 % P, 12 % S) at a rate equating to 200 kg P/ha, 58 kg K/ha and 20 kg S/ha to ensure that nutrients were non-limiting to pasture production. Applications of nitrogen (N) fertiliser were applied at a rate of 46 kg N/ha as urea (46 % N) after each destructive harvest.

3.2.2 Experimental design

The experimental design consisted of 9 treatments (1 dryland and 8 spray-irrigated [I1-I8]) arranged as a randomised block design with 3 replicates, resulting in 27 experimental plots of dimensions 2 m x 3 m, with a 2 m buffer in between each plot. The 8 irrigated treatments consisted of applying water at 3 different rainfall deficit thresholds, with depth of application 0, 10 and 20 mm below the potential amount required to refill the profile back to field capacity (Table 3.2). The rainfall deficit was calculated as the difference in PET minus rainfall. The PET was estimated as 0.8 x daily ‘Class A’ pan evaporation from the experimental site. Any watering event that increased the deficit above zero was classed as zero and not a positive value in the water balance sheet, as this additional water was assumed to be lost below the root-zone. A rainfall deficit of 20 mm represents 50 % of the readily available water for this soil type and is the current industry recommendation for maximising yields. The other 6 irrigation treatments which had thresholds below the 20 mm optimum were considered deficit irrigation treatments as they had the potential to expose plants to soil water stress.

Irrigation was delivered by a hand-held hose with pressure manually regulated at the tap to an average of 50 psi. This resulted in an average time of watering of between 6 min for the smallest application depth (10 mm) to 36min for the largest (60 mm). The average distribution uniformity of irrigation application was 79 %.

Table 3.2 Irrigation treatments identified by "Treatment name" (I1-I8), and specified according to the rainfall deficit (mm) at which an irrigation event occurred and the depth of application at each event (mm). The total number of irrigation events for each treatment is provided as well as the total amount of irrigation applied over the experimental period (mm).

Treatment name	Rainfall deficit trigger point	Depth of application	No. of irrigation events	Total amount of irrigation applied
I1	20	20	10	200
I2	20	10	17	170
I3	40	40	5	200
I4	40	30	5	150
I5	40	20	7	140
I6	60	60	2	120
I7	60	50	2	100
I8	60	40	3	120

3.2.3 Field measurements

3.2.3.1 Herbage dry matter production

A herbage sample (approximately 200 g fresh weight) was cut using hand shears to a residual standing height (RSH) of 50 mm at 3 random locations within each plot, immediately prior to a defoliation event. The herbage sample was weighed and dried at 60^{o}C for 48 h to estimate herbage DM percentage (DM %). The remainder of the plot was then cut using a rotary lawnmower to the same RSH and immediately weighed (plot fresh weight; FW). Plot DM was then calculated as DM % x FW to give total plot DM (kg DM/ha). The DM yield obtained at the commencement of the experiment on 12 January 2008 was used as a covariate. Subsequent harvests occurred at full emergence of 3 leaves per tiller or before canopy closure, which was considered the optimal time for defoliation (Fulkerson & Donaghy 2001). For the irrigated treatments a total of 4 harvests occurred, and although the dates of harvest varied between treatments due to variation in leaf appearance rate, all treatments were harvested within 2 weeks of each other and subsequently grouped according to "regrowth period" (P1-P4) to enable repeated measures analysis (Table 3.3). Only 3 harvests were possible in the dryland treatment due to water-stress induced senescence during the first period of the experiment.

Table 3.3 The timing of irrigation treatments, grouped into regrowth periods.

Regrowth period	Date of harvest	Treatment
P0	12 January – covariate	All
P1	12 February 18 February	I1-I2 I3-I8
P2	18 March 24 March	I1-I2 + dryland I3-I8
P3	23 April 5 May	I1-I2 I3-I8 + dryland
P4	25 June	All

3.2.3.2 Tiller density

Tiller density was assessed five times during the experiment, on 23 December (P0), 25 February (P1), 29 March (P2), 2 May (P3; I1-I2) and 12 May (P3; dryland and I3-I8), and 9 July (P4), and took place 1-2 weeks after a defoliation event. This was considered sufficient time for growth to have occurred in order to identify whether tillers were alive or dead, and to indentify daughter tillers. A replicate plot was subdivided into quarters, and a 0.006 m^2 quadrat was placed randomly within each of the four areas and the number of tillers (live mature and daughter tillers) recorded.

3.2.3.3 Tiller dynamics

At the commencement of the experiment, 5 tillers were marked with a coloured wire loop, evenly spaced along a diagonal transect across the full length of each plot. A mature vegetative tiller without visible daughters was initially selected for monitoring, and at 6 periods during the experiment (30 January, 24 February, 10 and 27 March, 9 and 27 April), the status of the tiller (live or dead, with or without a daughter tiller) was recorded.

3.2.3.4 Leaf extension

Three tillers per plot (= 9 per treatment), spaced 0.5 m apart, were marked with a coloured wire loop for monitoring of leaf extension every 3-4 days within the period 18 January to 27 April. Leaf length was measured with a ruler from the ligule to the tip on each leaf and the growth rate expressed as mm/tiller/day. In the event that a tiller died during a regrowth period, the extension rate was recorded as 0 mm/day until a harvest had occurred and a new tiller could be marked.

3.2.3.5 Botanical composition

Botanical composition was assessed non-destructively using a rod-point technique developed by Little & Frensham (1993), which is a simplified version of the point-quadrat method (Wilson 1960). The rod point consisted of a 50 cm metal rod with points at each end. Each plot was divided into 6 equal sections, and the rod was thrown randomly twice within each section and the botanical composition that each point touched was recorded. Botanical composition was divided into 5 categories – *Lolium perenne* L. (perennial ryegrass), *Dactylis glomerata* L. (cocksfoot), legume, broadleaf weeds and other grasses. In the event that either point touched bare ground, the rod was thrown again. Species abundance was expressed as a percentage based on the total number of "hits" possible (24 per plot). Assessment occurred on the same days as tiller density.

3.2.3.6 Nutritive value of herbage and water soluble carbohydrates of stubble

The nutritional value of the herbage and energy status of the stubble was analysed at four points in the experiment (P0, P2-P4), for selected treatments, dryland, I1, I3 and I6. Herbage samples collected before harvest for DM content were ground through a 1mm sieve and analysed for neutral-detergent fibre (NDF), total N, digestibility of organic DM (DOMD) and digestible DM (DDM) concentration using near-infrared (NIR) spectrometry at Agrifood Technology FeedTEST laboratories, Victoria, Australia (AFIA 2009). NIR spectra were collected using a Foss-NIR systems 5000 scanning monochromators (Foss Electric, Silver Spring, MD, USA) in conjunction with Infrasoft International software. NIR calibrations for N were previously derived using the Kjeldahl method (AFIA, Method 1.4R), for NDF concentrations using the method of Van Soest and Wine (1967) and ANKOM equipment (AFIA, Method 1.9Aa), and for DDM using a pepsin-cellulase technique, with analytical values adjusted using a linear regression based on similar samples of known *in vivo* DDM (Clarke *et al.* 1982) (AFIA, Method 1.7R).

Digestibility of organic matter was calculated using the following formula: DOMD% = 6.83 + 0.847 DMD (%) (r^2 = 0.93; s.e.m. = 2.67) (Kaiser *et al.* 2005). Metabolisable energy (ME) values were calculated from estimated DOMD values using the formula: ME = (0.203 x DOMD %) – 3.001 (Kaiser *et al.* 2005). Crude protein (CP) concentration was calculated by multiplying the N concentration by 6.25.

On the same day as herbage samples were collected, stubble samples (tiller material below 50 mm mowing height) from 5 randomly selected plants from each plot were harvested to ground level with a scalpel and leaves removed above 50 mm. Samples were collected no later than 3 h after sunrise to negate the confounding effect of diurnal fluctuations in water soluble carbohydrate (WSC) content (Fulkerson & Slack 1994). Samples were transported on ice to minimise loss of WSC reserves through respiration and then frozen at -20^{o}C for 48 h before freeze-drying. Following freeze-drying, the number of tillers in a sample (5 plants bulked per plot) were recorded. The samples were then ground to pass through a 1 mm sieve and analysed for WSC content. The WSC concentration (mg g^{-1} DM) was determined by cold extraction in a reciprocal shaker for 1 h using 0.2 % benzoic acid-water solution, and the hydrolysation of the cold water carbohydrates extracted by 1 mol L^{-1} hydrochloric acid to invert sugars. This solution was heated at 90^{o}C, the sugar dialysed into an alkaline stream of potassium ferricyanide, and reheated to 90^{o}C before determining WSC concentration using an autoanalyser (420 nm; Technicon Industrial Method number 302-73A; modified from the method described by Smith (1969)).

3.2.3.7 Root dry matter

Within 3 days of the second harvest (P2), three soil cores were taken from each plot to determine perennial ryegrass root mass. The corer (40 mm diam.) was placed over the centre of a randomly selected clump of perennial ryegrass plants and each core taken to 0.6 m depth and cut into 5 depth classes: 0-5 cm, 5-10 cm, 10-15 cm, 15-20 cm, 20-30 cm, 30-60 cm. Roots were washed free of soil in portions using a series of sieves and dried at 80^{o}C for approximately 24 h to determine root DM yield.

3.2.3.8 Water use indices

Three water use indices as defined by Purcell and Currey (2003) were used to compare water use efficiency between treatments. The gross production water use index (GPWUI) was calculated as the total production/total water applied (irrigation plus rainfall); the irrigation water use index (IWUI; 'irrigation efficiency') was calculated as total production/irrigation water applied; and the marginal irrigation water use index (MIWUI) was calculated as marginal production due to irrigation (irrigated yield-dryland yield)/irrigation water applied.

3.2.4 Statistical analysis

Mixed model analysis of variance was performed using proc mixed procedures from the SAS statistical package, version 9.1 (SAS Institute Inc., Cary, NC, USA). For the analysis of quality parameters – CP, NDF and the ME of herbage DM and the yield parameters WSC and tiller density, plot replicates were assigned a random effect. These variables, whilst sampled at multiple time points, were considered independent, as measurements were made at each interval on a randomly selected plant sample. Treatment effects of the 9 different irrigation practices on total DM yield and associated water use indices were also analysed by this method. Where a significant effect was detected, Tukey-Kramer (Kramer 1956) was used for pairwise comparisons and significance accepted when $P<0.05$.

Problems with normality of residuals were identified in the analysis of water use indices. In the case of the IWUI, a log transformation was applied and the least square means back-transformed for reporting of estimates. However for the GPWUI and MIWUI, differences between means were unable to be detected despite a significant *P*-value, and even when transformed. An outlier was identified and removed for reporting of estimates and pairwise comparisons. The *P*-value reported in all cases is from the analysis of raw unmodified data.

Tiller dynamics, DM production and ME per ha were monitored either on particular plants or at the whole plot level, and therefore measurements are likely to be correlated in time. In this case repeated measures were additionally employed to mixed model analysis of variance, with the use of a covariance structure to specify the relationship among residuals. To select the most parsimonious covariance model, a log likelihood ratio chi-square test was used to compare nested models. The *P*-value for model selection was derived from the difference in the -2 log likelihood statistics between two models, assuming chi-square distribution with degrees of freedom given by the difference in the number of parameters between models.

Where there was no significant difference, the reduced model was selected. Akaike's Information Criterion (AIC) (Akaike 1974) and biological reasonableness was used to distinguish between non-nested models.

No statistical analyses were performed on the botanical composition data as ryegrass remained >50 % in abundance at all time samples. Tiller dynamics was analysed by a generalised linear model with Poisson distribution using the Generalised Estimating Equation procedure to model time correlates (Diggle 1994). The pattern in daughter tiller initiation and rate of tiller death over time were modelled independently and then combined to determine if the rate of change was significantly different between the two categories.

For testing whether deficit irrigated plants experienced more water-stress induced reductions in leaf elongation as well as the capacity for compensatory growth, the distribution of observations above, below and in between the 25^{th} and 75^{th} percentiles of plants grown under the industry practice were compared. Significance was based on a chi-square test analysed using proc freq, and then the *P*-values adjusted for multiplicity using proc multtest.

Figures were constructed using Sigmaplot (SPSS Inc., Chicago, IL, USA).

3.3 Results

3.3.1 Dry matter yield

There was a significant (*P*<0.001) interaction between irrigation treatment and time with differences between well-watered and deficit treatments only significant at P1 and P3 (Fig. 3.2). The dryland growth rate at P2 was significantly different to all irrigated treatments, but by P3 had recovered to the average growth rate of the deficit irrigation treatments (I3-I8). The growth rates of the deficit irrigation treatments remained similar within each regrowth period, with an overall decrease in growth rates over time.

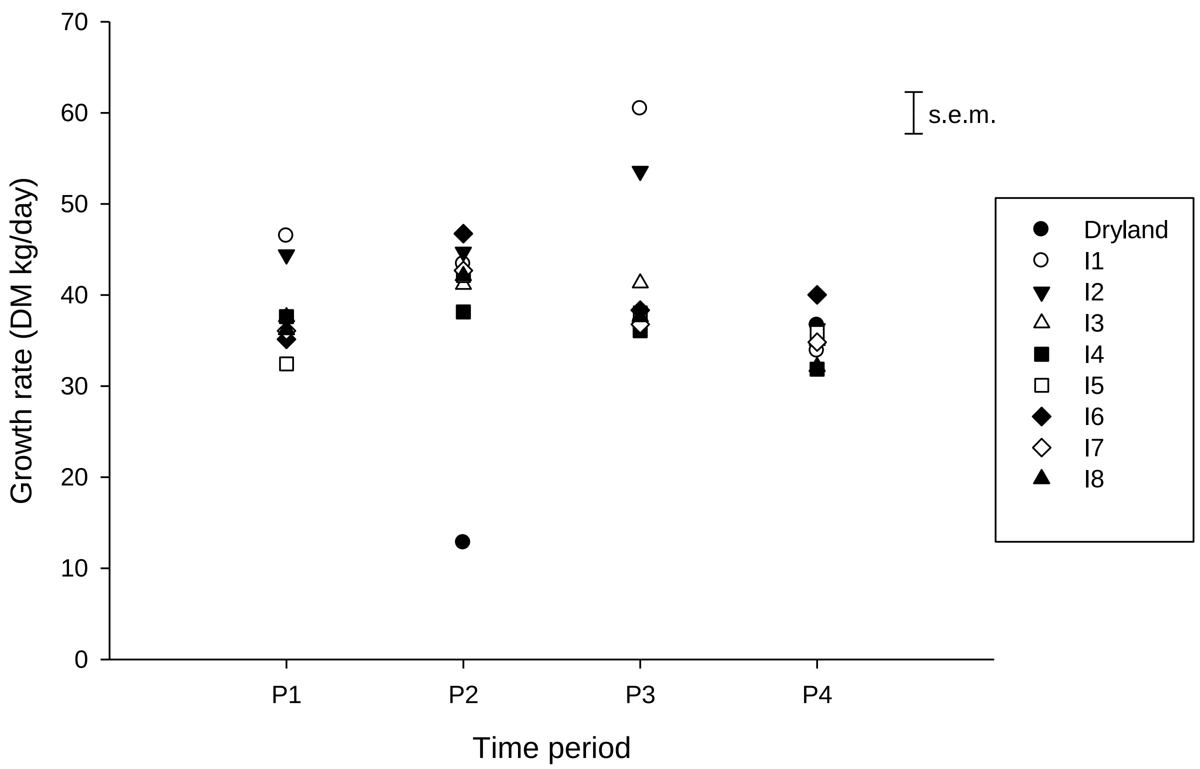


Figure 3.2. Least squares means of growth rates for the irrigated (I1-I8) and dryland treatments over each of the four regrowth periods (P1-P4). Growth rate was calculated as the dry matter (DM) yield at the end of a regrowth period divided by the number of days in that regrowth period. The vertical bar indicates the standard error of the mean (s.e.m = 2.29).

In terms of total DM produced, there was an overall treatment effect (Table 3.4). The well-watered treatment, I2, observed the highest yield of 7.25 t DM/ha compared with the dryland treatment which had the lowest yield of 4.48 t DM/ha. Importantly, there was no significant reduction (P>0.05) in DM yield between the deficit irrigation treatments (I3-I8) and the well-watered treatments (I1 and I2), except for I4 and I8.

Table 3.4 Mean total herbage harvested (t dry matter (DM) ha^{-1}), irrigation applied and the gross production water use index (GPWUI), marginal irrigation water use index (MIWUI) and irrigation water use index (IWUI) (t DM/ML) for each of the irrigation treatments (I1-I8), over the experimental period (Jan 13-June 25 2009). The industry average GPWUI is presented for comparison. Irrigation savings (ML/ha over experimental period) with reference to the industry practice I1 are also given. Letters within columns indicate means which are significantly different at P=0.05.

Treatment	Total DM yield	Irrigation applied	GPWUI	MIWUI	IWUI	Irrigation savings
dryland	4.48^{c}	3.9 (rainfall)	1.15^{ab}			
I1	7.23^{a}	2.0	1.22^{ab}	1.35^{ab}	3.54^{de}	
I2	7.25^{a}	1.7	1.29^{a}	1.59^{a}	4.16^{cd}	0.3
I3	6.31^{ab}	2.0	1.07^{b}	0.92^{b}	3.15^{e}	0.0
I4	5.83^{b}	1.5	1.08^{b}	0.90^{b}	3.89^{cd}	0.5
I5	6.06^{a}	1.4	1.15^{ab}	1.13^{ab}	4.33^{c}	0.6
I6	6.54^{ab}	1.2	1.19^{ab}	1.31^{ab}	5.42^{ab}	0.8
I7	6.11^{ab}	1.0	1.25^{a}	1.63^{a}	6.10^{a}	1.0
I8	5.99^{b}	1.2	1.18^{ab}	1.26^{ab}	4.99^{bc}	0.8
s.e.m.	0.24		0.03	0.12	0.04 (log scale)	
P-value	<0.0001		<0.05	<0.05	<0.0001	
Industry ave.			1.00$^{\#}$			

$^{\#}$ Rawnsley *et al.* (2007)

3.3.2 Water use indices

There was a significant effect (P<0.05) of the irrigation practice on all estimated water use indices (Table 3.4). The greatest difference between treatments was observed for IWUI with the highest estimate observed for I7 (6.10 t DM/ML) and the lowest for I3 (3.15 t DM/ML). The MIWUI of I2 and I7 were significantly higher (P<0.05) than I3 and I4, whereas all other treatments were intermediate and not significantly different (P>0.05) from each other. The improved MIWUI of the deficit irrigation treatment I7 resulted in the maximum water saving of 1 ML/ha compared with the industry practice I1, without impact to the yield potential. This was followed closely by I6 and I8, with a water saving of 0.8 ML/ha.

The least differentiated of the water indices was the GPWUI with an overall average of 1.17 t DM/ha. Notably, the highest GPWUI was observed for the deficit irrigation treatment I8 and the well-watered treatment I2, compared with I3 and I4 which were significantly (P<0.05) lower.

3.3.3 Yield components

Tiller density declined over time from a mean of 8545 tillers/m^2 (highest mean; P1) with a significant reduction (P<0.001) observed after the fourth harvest to a mean of 6672 tillers/m^2 by P4 (Fig. 3.3). There was also a significant decline (P<0.001) in tiller initiation and death over the experimental period, which was consistent across treatments (Fig. 3.4). However, whilst the rate of tiller death tended to decrease at a faster rate than tiller initiation between sample periods, the slopes of the log linear regressions between each category weren't significantly different (P>0.05; Fig. 3.4).

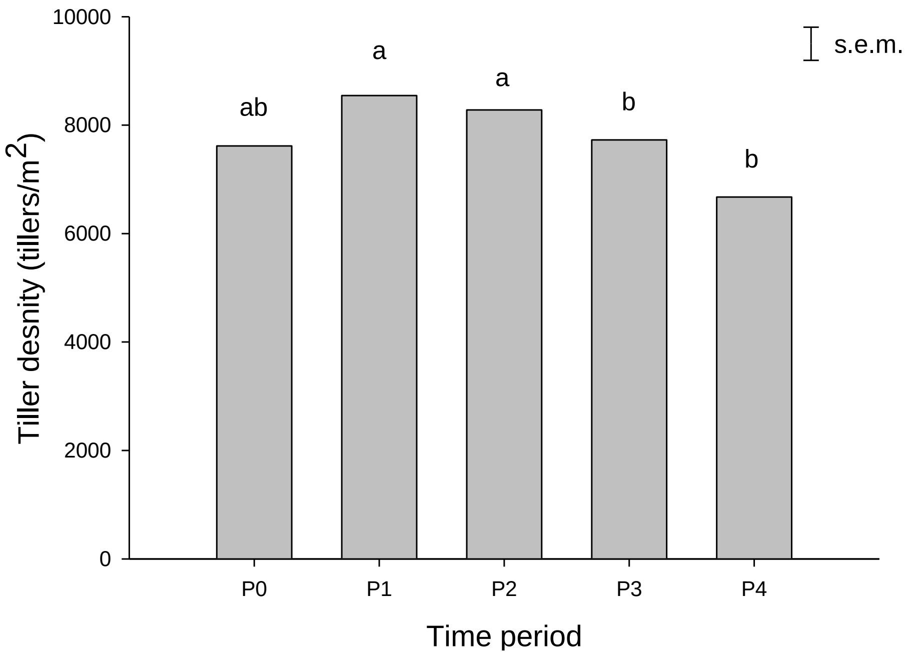


Figure 3.3 Least squares means of tiller density across all treatments, sampled 1-2 weeks after a harvest period (P0 refers to the regrowth period prior to the commencement of the experimental treatments). Letters indicate significant difference between means (P-value < 0.001), with standard error of the mean (s.e.m = 307) represented by the vertical bar.

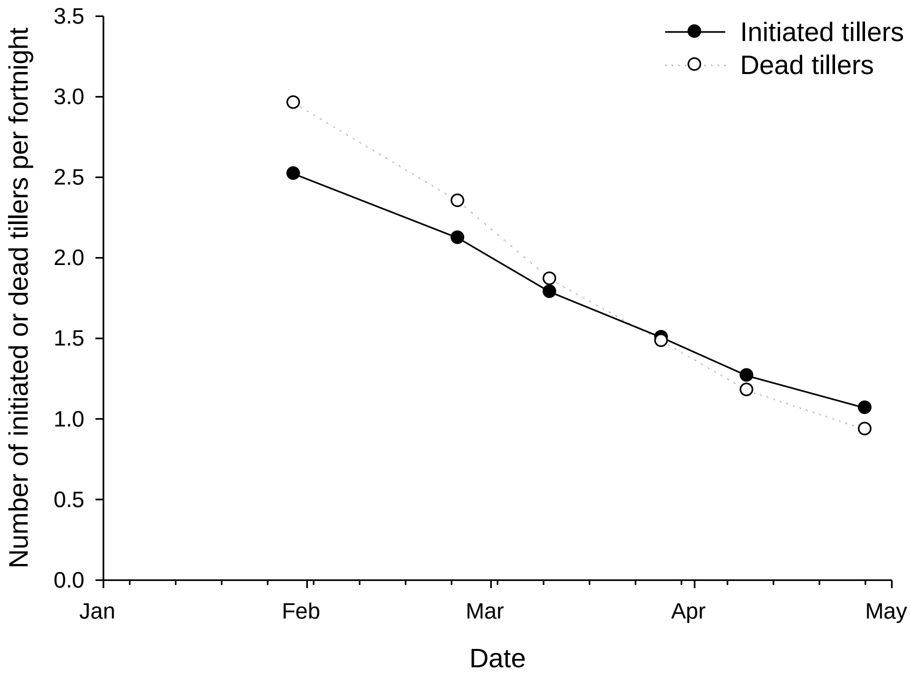


Figure 3.4 Least square means of the number of tillers that had initiated (closed circle) or died (open circle) per fortnightly sampling over the experimental period (30 Jan. to 27 April 2009), across all treatments.

Tiller DM within the selected treatments (dryland, I1, I3 and I6) significantly decreased (P<0.001) over time from a mean of 33.61 mg/tiller at P2 to a mean of 20.15 mg/tiller at P4 (Table 3.5). Despite the comparable tiller weights between treatments, tiller WSC content varied significantly (P<0.01) between time and treatment and subsequently stubble WSC concentration (P<0.001; Table 3.5). Furthermore as a determinant of subsequent DM potential, WSC content was a poor predictor of DM variation between treatments (r^2 = -0.0075, data not shown).

Table 3.5 Least square means of stubble water-soluble carbohydrate (WSC) concentration (mg g^{-1} dry matter (DM)) and content (mg/tiller) for plants harvested at the commencement of the experiment (reference level P0), and at subsequent harvest periods (P2-P4) across a selection of deficit irrigation treatments with increasing rainfall deficit (I1-20mm; I3-40mm and I6-60mm), and a dryland treatment. For reference, a "target" level of WSC demonstrated to ensure optimal yields in the proceeding regrowth is >6.5. Mean tiller DM (mg) for each harvest period is also listed. Standard errors of the mean and P-values are presented for the interaction between time and treatment (P<0.05).

	Stubble WSC concentration tiller^{-1}				Stubble WSC content tiller^{-1}				Tiller DM
Time	Dryland	I1	I3	I6	Dryland	I1	I3	I6	
P0	18.57	14.57	13.80	14.83	3.60	2.79	2.46	2.55	18.45[a]
P2	17.20	21.53	23.13	24.13	5.55	7.73	8.35	7.32	33.61[b]
P3	34.80	18.20	25.33	26.10	7.90	4.84	7.12	6.41	25.77[c]
P4	29.37	30.17	23.97	27.23	4.79	7.10	3.74	6.70	20.15[a]
s.e.m.				2.40				0.67	1.42
P-value				<0.01 (treat*time)				<0.001 (treat*time)	<0.001 (time)
Target								>6.5[#]	

[#] Lee *et al.* (2008)

In terms of the growth potential of foliage, all deficit irrigation treatments including the dryland treatment, except for I5, observed a shift in the distribution of leaf elongation rate with significantly (P<0.05) more observations lower than the 25th percentile for plants grown under the industry irrigation practice (I1), and less above the 75th percentile (Fig. 3.5). This suggests these plants experienced water-stress induced reductions in leaf elongation more often than plants subject to the industry irrigation practice and this was not compensated for by additionally higher rates of leaf elongation in response to watering. Instead however, leaf elongation rate was contracted to a greater degree within the 50th percentile, resulting in an overall non-significance (P>0.05) of mean leaf elongation rate compared with I1 and I2 (Table 3.6).

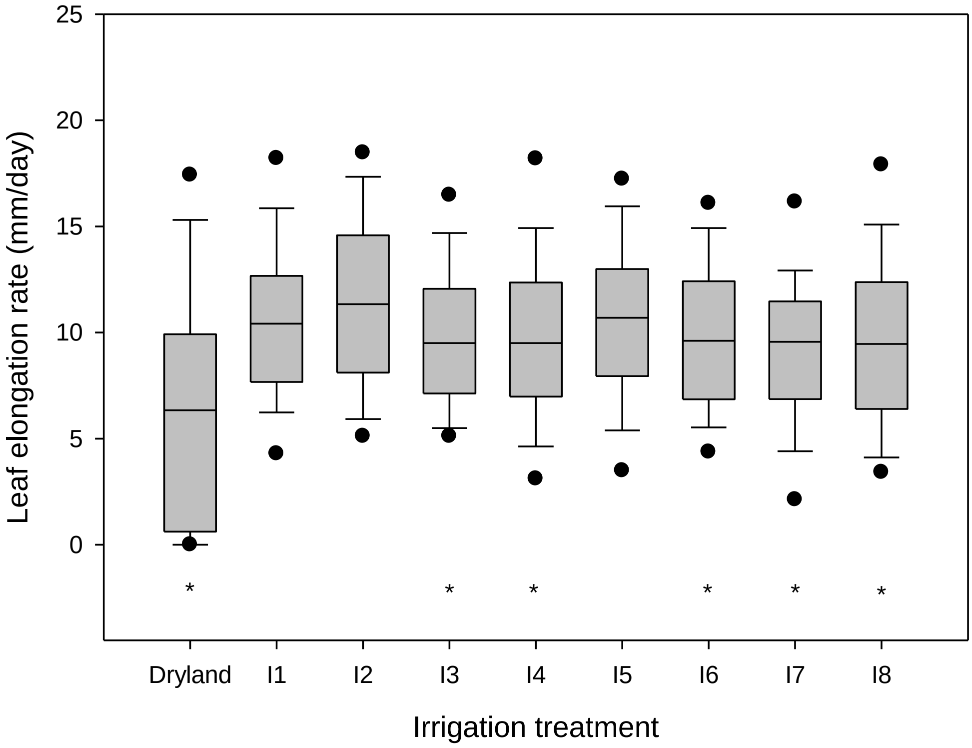


Figure 3.5 Box-plots of the distribution of leaf elongation rate monitored on tillers from 18 Jan to 27 April 2009. 50 % of the data are contained in the box, with the middle line indicating the data median. The upper and lower edges of the box represent the 25th and 75th percentiles respectively, and the whiskers the 10th and 90th percentiles. The 5th and 95th outlying points are also given. Asterisks indicate where the distribution of observations significantly differs (P<0.05) from plants grown under the industry irrigation practice (I1).

Table 3.6 Least square means of leaf elongation rate (mm/day) for the period 18 January to 27 April 2009 with respect to the irrigation treatments. Standard error of the mean (s.e.m.) and the *P*-value are presented, with significant differences between treatments represented by letters.

Treatment	Mean leaf elongation rate
dryland	6.34[b]
I1	11.46[a]
I2	10.76[a]
I3	10.77[a]
I4	9.87[ab]
I5	10.04[ab]
I6	9.67[ab]
I7	9.13[ab]
I8	9.74[ab]
s.e.m.	0.81
P-value	<0.05

There was no significant effect (P>0.05) of irrigation practice on either the total root DM production within a 60 x 4 cm core, or the distribution of roots at depth (data not shown) by P2, with approximately 50 % of the roots located in the first 5cm of the soil with an average root mass density of 0.01 g DM/cm^3 (0.8 x 10^{-3} s.e.m.), (Fig. 3.6).

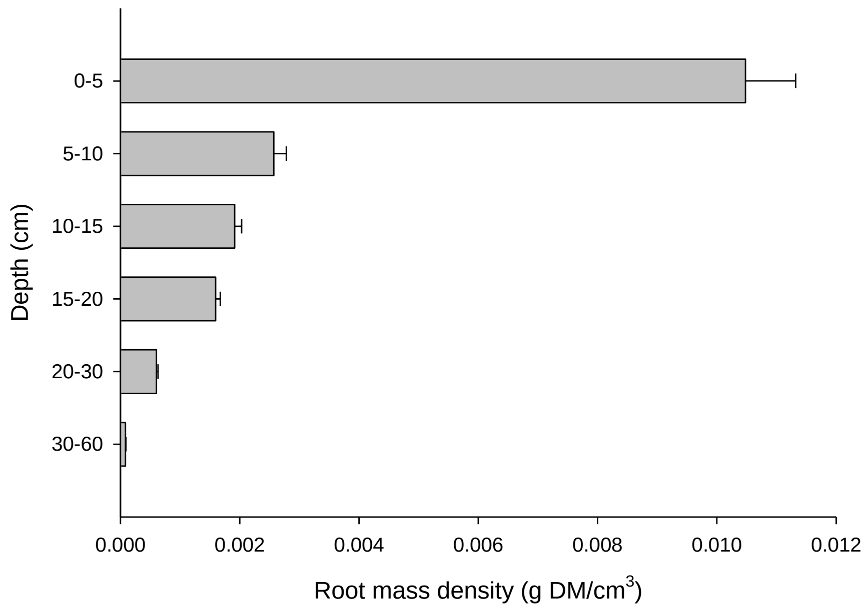


Figure 3.6 Average root mass density at depth, sampled at regrowth period, P2. Approximately 50% of the roots are located in the first 5 cm of the soil with an average root mass density of 0.01 g DM/cm^3. Horizontal bars represent standard errors of treatment means.

3.3.4 Herbage nutritive value

There was a significant interaction (P<0.05) between harvest period and irrigation treatment for ME concentration, with a general trend towards increasing ME concentration over time (Table 3.7). Neutral detergent fibre followed a similar but opposite trend to ME concentration, with higher levels within a treatment corresponding to lower ME concentrations and vice versa (Table 3.7). However this pattern was restricted to individual treatments with the strength of the relationship varying. Thus in general, NDF alone was a poor predictor of ME concentration (data not shown). Harvest period was the only effect on CP, with levels increasing over time from 185.3 g kg^{-1} DM at P0 to 221.7 g kg^{-1} DM at P4 (Table 3.7). There was no significant (P<0.05) effect of the irrigation treatment on CP levels.

Perennial ryegrass remained the dominant species throughout the experimental period, with a mean of 79 % (0.09 s.e.m.) perennial ryegrass on a DM basis, followed by cocksfoot with a mean of 17 % (0.84 s.e.m.), legume 3 % (0.45 s.e.m.) and broadleaf weeds 2 % (0.23 s.e.m.).

Table 3.7 Least square means of the amount of estimated metabolisable energy (ME; MJ kg^{-1} dry matter (DM)), neutral detergent fibre (NDF; % DM) and crude protein (CP; g kg^{-1} DM) for plants harvested at the commencement of the experiment (P0) and subsequent harvests (P2-P4), across a selection of deficit irrigation treatments with increasing rainfall deficit (I1-20mm; I3-40mm and I6-60mm), and a dryland treatment. Target levels of nutritive constituents are presented for comparison. Standard errors of the mean and P-values are presented for the interaction between time and treatment for ME and NDF, and the time response for CP.

	ME				NDF				Crude
Time	**Dryland**	**I1**	**I3**	**I6**	**Dryland**	**I1**	**I3**	**I6**	**protein**
P0	12.03	12.17	12.30	12.13	47.03	47.67	43.80	44.87	185.3^{c}
P2	12.00	12.13	11.93	11.90	46.50	47.63	47.10	45.23	196.9^{b}
P3	12.63	12.03	12.57	12.57	45.40	49.13	43.23	48.73	205.6^{b}
P4	12.37	12.20	12.53	12.60	46.83	48.73	43.10	43.37	221.7^{a}
s.e.m.				0.123				0.8419	4.10
P-value				<0.05 (treat*time)				<0.01 (treat*time)	<0.001 (time)
Target				12[#]				38-45[##]	120-180[###]

[#] Waite *et al.*(1964)
[##] Kolver (2000)
[###] Jacobs & Hargreaves (2002)

3.4 Discussion

Reductions in water use at the leaf level are achieved through decreasing stomatal conductance. In Chapter 2, perennial ryegrass was demonstrated to have the ability to restrict daily water use without impact to DM yield under the levels of water deficit tested. However because of the tight link between transpiration and biomass production, improvements in WUE are considered to be conservative, especially in an aerodynamically smooth crop such as pastures where there tends to be poor coupling between transpiration and stomatal conductance (Jarvis & McNaughton 1986). At the canopy level however, because water availability is dependent on a largely unpredictable rainfall source and a determinable irrigation source i.e. it can be managed, improvements to irrigation efficiency can be targeted to a greater extent through scheduling practices that better match plant water requirements. Over-watering and reduced rainfall utilisation are two common problems of poor irrigation management.

In the current study, a regulated deficit irrigation scheme, using a rainfall deficit to schedule irrigation events, was assessed to improve the potential for rainfall capture. It was found that not only could irrigation efficiency be improved through practising deficit irrigation, but that this could be achieved largely without penalty to yield or pasture quality. Where there was a significant decrease in yield, this was observed in the deficit irrigation treatments which maintained the soil profile at a constant deficit. Despite there being no apparent risks associated with increasing the rainfall deficit from 20 mm to 60 mm before triggering irrigation, the achievable water-savings and therefore the applicability of the deficit irrigation strategy, is likely to be dependent on annual rainfall. Reasons as to why a yield penalty was not observed are discussed, as well as limitations to the irrigation scheduling approach tested, and opportunities for continued development of the deficit irrigation concept.

3.4.1 Effect of deficit irrigation on yield components and herbage quality

Leaf elongation is one of the most sensitive yield components of grass plants to water deficits (Norris & Thomas 1982a; Thomas *et al.* 1999), decreasing in response to reduced turgor pressure as Ψ_{leaf} declines. As a sensitive indicator of water stress, it has been successfully used to schedule irrigation events (e.g. Inman-Bamber 1995; 2004) and screen grass species for drought resistance (e.g. Wang & Bughrara 2008). Despite the fact that the rainfall deficits ranged from 20 mm to 60 mm before irrigation was triggered, average leaf elongation rates were similar between irrigated treatments (Table 3.6), suggesting that either the soil water deficit was not sufficient to cause significant decline in leaf water potential, or turgor maintenance through processes such as osmotic adjustment were occurring (Hsiao *et al.* 1976; Jones *et al.* 1980).

Assimilation is considered less sensitive than leaf growth, and is likely to be the reason why WSC stores initially increase under mild water stress (Chaves 1991; Thomas & Evans 1989). On rewatering, the accumulation of WSC has been implicated in the capacity of plants for compensatory growth, where the rate of leaf elongation exceeds that of plants not subjected to drought (Corleto & Laude 1974; Horst & Nelson 1979; Korte & Chu 1983). The accumulation of WSC have also been closely linked more generally to regrowth potential in relation to recovery from drought (Volaire 1994) and defoliation (Donaghy & Fulkerson 1997; 1998). This was one hypothesis tested here, however whilst the treatment-time interaction for WSC was significant (P<0.05), the pattern of change was not distinct (Table 3.5). Furthermore WSC content was a poor predictor of subsequent yield potential (r^2 = -0.0075, data not shown)

Lee *et al.* (2008) determined that DM yield could be maximised using different grazing strategies if a WSC content per tiller of >6.5mg was achieved. In the current study, WSC levels ranged from 2.79 to 8.35 mg/tiller (Table 3.5). The lack of a relationship between WSC levels and regrowth potential suggests that the effect of water availability is far more dynamic than was able to be captured from one sampling point during a regrowth period. Furthermore, the DM of tiller bases were also comparable between treatments (Table 3.5), suggesting that the energy storage capacity of the plant was not affected by the irrigation treatments.

Under mild water stress, whilst the rate of tiller death has been found to be comparable to well-watered controls, the rate of tiller appearance tends to be reduced under water deficits, resulting in a net decline in tillers (Barker *et al.* 1985; Jones *et al.* 1980; Korte & Chu 1983). No significant difference (P>0.05) between irrigation treatments was found between the rate of daughter tiller initiation and death (Fig. 3.4), which correspondingly resulted in similar tiller densities (Fig. 3.3). The general rate of decline in both tiller initiation and density over the experimental period is most likely due to the effect of decreasing temperatures on the rate of leaf appearance (Mitchell 1953; Silsbury 1970) and hence number of potential tiller sites

(Davies 1974). This was further observed in the general decline in growth rates over the experimental period (Fig. 3.2).

Under continued soil drying, further decreases in the evaporative surface of plants occur through progressive senescence or dieback from leaf tips (Humphreys & Thomas 1993). Reliance on WSC stores increases to support respiration processes, and thus WSC tends to decline under severe water stress and tiller death ensues (Thomas 1991; Volaire 1994; 1995). Browning off of pastures or leaf dieback is often observed in dryland pasture production, resulting in reduced WUE. This was visually observed in the dryland treatment during P1. However, because there were few rainfall inputs during this time, GPWUI remained similar to the irrigated treatments (Table 3.4), i.e. the growing period was effectively shortened.

Water stress can also cause an immediate reduction in root extension (King & Bush 1985), although in the long term, roots of plants infrequently irrigated tend to penetrate deeper in soil than roots of regularly irrigated plants (Jupp & Newman 1987), however total root mass does not always increase (Assuero *et al.* 2002). Enhanced rooting depth of plants subjected to water stress may lead to greater total water access relative to plants not subjected to stress, thus increasing WUE. However, no differences between treatments were found for either total root DM or for root distribution pattern (Fig. 3.6) that could be implicated in the different GPWUI observed between treatments (Table 3.4).

The nutritive value of pasture is also an important aspect of pasture production, being a key determinant of feed intake by ruminants and energy conversion for milk production (Minson 1987). Changes in herbage quality can be partly due to changes in botanical composition as a result of the differential sensitivity of species to water stress. For example, ryegrass tends to out-compete white clover under water stress due to a larger root system and more efficient control of transpirational losses (Lucero *et al.* 1999). In the current study, there was no effect of irrigation treatment on pasture composition, with ryegrass remaining the dominant component at a mean of 79 % of total pasture DM throughout the experimental period, followed by cocksfoot (17 %), legume (3 %) and broadleaf weeds (2 %).

In terms of the direct effects of water stress on herbage quality attributes, rate of senescence and lignification of leaves and sheaths tend to increase, inflating NDF values, which subsequently reduces the ME value of the herbage through its effect on voluntary intake (Casler & Vogel 1999). When growth rates reduce, the concentration of leaf N, and subsequently CP, generally increases. Jensen *et al*. (2003) indicated that the nutritive value of cocksfoot and perennial ryegrass could be increased under water stress, observing near linear increases in CP with decreasing irrigation inputs without the obvious increase in NDF. However these nutritive advantages were negated by the associated decline in DM yield. Despite the detection of significant interactions between treatment and sampling time in the current study, the nutritive constituents ME, CP and NDF remained within the ranges considered to be of optimal quality across all treatments [>11.5 MJ ME kg^{-1} DM, 38-45 NDF % DM (Kolver 2000); 120-180 CP g kg^{-1} DM, (Jacobs & Hargreaves 2002)] (Table 3.7).

Although no differences were observed in the yield components leaf elongation, tiller density or root mass of deficit irrigated plants, there was a significant effect ($P<0.001$) of irrigation practice on total DM yield for the experimental period (Table 3.4). However, significant reductions compared with the well-watered treatments (I1 and I2), were only measured in the deficit irrigated treatments I4 and I8. Differences in scale and plot heterogeneity can in part explain discrepancies between patterns in yield components and total DM yield. However, in terms of the physiological reasoning as to why particular deficit irrigated treatments performed differently is less obvious, especially as in the case of treatment I8, the same amount of water was applied as in treatment I6 which grew 0.55 t DM/ha more, and I4 received the second highest amount of water amongst the deficit irrigated treatments (I3-I8) (Table 3.4).

One possible explanation is that both exposure to water stress and partial rewatering may have induced the production of the plant hormone abscisic acid (ABA). Abscisic acid has been implicated in the regulation of stomatal conductance in order to prevent successive falls in leaf water status under conditions where water availability is stratified within the soil profile (Davis *et al.* 2002), or by ensuring complete recovery of the water transport system (Lovisolo *et al.* 2002; 2008). A similar argument was provided to explain the lack of preferential use of water during the first few daylight hours of plants subjected to a restricted nightly watering regime in Chapter 2. Presumably however, this mechanism would have been effective across all the deficit irrigated treatments.

Just as important is the converse question of why 4 of the 6 deficit irrigated treatments performed equally as well as the well-watered treatments, with water savings of up to 1 ML/ha achieved (Table 3.4). Two possibilities are provided for this observation – the first being that leaf level WUE was increased. The evidence to support the potential for perennial ryegrass to augment WUE was demonstrated in Chapter 2. Direct measures of plant water use were not obtained in the current study, so comparison between glasshouse and field achievements cannot be made. However the implications for improvements in irrigation efficiency at the canopy level are further discussed under the section "assessing improvements to irrigation practices". The second possibility, which is in contrast to the first, is that the level of water stress at a rainfall deficit of 60 mm was not enough to cause reductions in growth. The latter situation will be considered through a discussion on the "limitations of the irrigation scheduling approach" utilised in the current study.

3.4.2 Limitations of the irrigation scheduling approach

Irrigation scheduling is conventionally based on direct or indirect estimates of soil water depletion according to the basic understanding that not all water held within the soil profile is easily extractable by plants (Ritchie 1981). The amount of water that can be depleted before water uptake becomes limiting to growth is defined as readily available water (RAW) or "allowable depletion" (Allen *et al.* 1998; Doorenbos & Kassam 1979), and is commonly taken to be 50 % of the water held between field capacity and the plant's wilting point (100% = total plant available water). In the current study, both soil water depletion and the RAW threshold were estimated and thus may have been subject to cumulative errors, resulting in an over or under estimation of consumptive water use (Jones 2004).

In using the water balance approach of inputs and outputs, over-estimation of plant water use is likely to have occurred as the ratio between actual ET and PET (output parameter) fluctuates due to the dynamic response of stomata to leaf water status, with most significantly, a general decline in the ratio observed under depleting soil water availability. Overestimation of consumptive water use can lead to overwatering, where more water is applied than the root-zone soil can hold, resulting in subsequent losses via deep drainage (Hsiao *et al.* 2007). In this situation, applying water to less than the full ET needs of the pasture may have improved the irrigation application efficiency relative to those treatments that aimed to fill the soil profile back to field capacity. The absence of a treatment effect for the growth attributes suggests that water use was similar, but that deep drainage differed, between the irrigated treatments.

The FAO-56 dual crop coefficient procedure (Allen *et al.* 2005) provides the opportunity for greater precision in estimating ET by separating evaporation and transpiration processes, and adjusting for plant stress resulting from salinity or soil drying. Greenwood *et al*. (2009)

found good correlation between estimated and measured soil water changes for perennial ryegrass using the dual crop method. However, whilst general coefficients and plant-water relationships are available (Allen *et al.* 1998), there is still the requirement for measurement of runoff and crop height, as well as for daily adjustment of basal crop coefficients according to variation in wind speed and minimum relative humidity from standard conditions. Therefore, PET obtained from meteorological sources tends to be more practical and user-friendly by farmers.

In terms of the broad application of fixed RAW thresholds for irrigation scheduling, evaporative demand, root distribution, soil-water hysteresis and soil texture have all been shown to influence the plant response to water availability and therefore the relative soil water depletion at which plant growth declines (Girona *et al.* 2002; Sadras & Milroy 1996; Sinclair *et al.* 1998). Hysteresis in the relationship between soil water availability and leaf water status makes applying generalised relationships of growth responses to average root-zone soil water content similarly difficult (Jones 2004). The ability of a plant to utilise either intermittent rainfall events or conversely larger irrigation events during water stress, depends on the requirements for recovery of growth processes, as well as root distribution patterns (Schwinning & Ehleringer 2001). In some woody tree species for example, recovery of water transport capacity may take days (Brodribb & Cochard 2009) compared with herbaceous plants, in which recovery can occur overnight (Neufeld *et al.* 1992; Stiller *et al.* 2003).

Differences in recovery rates of leaf elongation between forage species have been observed (Norris & Thomas 1982b), as well as compensatory growth (Horst & Nelson 1979; Ludlow & Ng 1977). Although there was no evidence of compensatory growth in the current study (Fig. 3.5), it is likely that plants subjected to deficit irrigation treatments had the capacity to utilise intermittent rainfall events and respond to irrigation without delays in recovery. This response would be in line with findings in Chapter 2, whereby a water deficit capable of reducing the plant's ability to transport water by 95 % could be incurred before recovery of gas exchange to pre-drought potential exceeded more than 1 day. Furthermore, despite the average soil water content of some plants being sufficiently dry to cause midday stomatal closure, nightly watering of restricted amounts were still able to be utilised. Therefore this would suggest that average soil water content may be a poor predictor of growth potential, particularly where water is available at the surface where the majority of roots are found. Further assessment of perennial ryegrass recovery processes in terms of capacity to utilise pulsed water inputs in the field, would be useful in understanding WUE in dryland pastoral systems and therefore the minimum requirements for deficit irrigation to ensure a high marginal response to water inputs.

3.4.3 Assessing improvements to irrigation practises

Water use indices are often used to compare the relative improvements in irrigation practices. However as a ratio of DM yield to water inputs, such indices can be limited in interpretation if presented alone. For example, there is an inherent tendency for WUE to increase with reductions in water inputs, but this is usually to the detriment of DM yield. Therefore, in a farming system, the water savings may be redundant if the cost of brought-in fodder is greater than the cost of the additional water requirements. That aside, water use indices are useful tools for benchmarking the value of water across different environments and management strategies.

The GPWUI provides an overall assessment of whether the expected yield returns are being achieved and therefore highlights the possibility for improved management and irrigation application and scheduling technologies. In the current study, the irrigation treatment had a significant effect on GPWUI (Table 3.4). However, values remained within the recorded industry average for Tasmania of 1-1.2 t DM/ML (Rawnsley *et al.* 2009), and similarly in other regions of Australia including northern Victoria (Armstrong *et al.* 2000; Lawson *et al.* 2007) and Queensland (Callow & Kenman 2004). The IWUI is very similar to the GPWUI, however due to scaling effects it more clearly highlights differences in irrigation inputs. As expected, IWUI increased with decreasing irrigation inputs (Table 3.4).

Over the experimental period a maximum saving of 1 ML/ha was possible. According to the 2004-05 ABS Water account there was approx 20 000 ha of irrigated dairy land in Tasmania, with a mean application rate of 4.3 ML/ha (ABS 2006). A saving of 1 ML/ha across all irrigated farms would therefore equate to 20 000 ML or a 23 % saving of irrigation water. Based on the 2007-08 estimated gross production economic water use index of $2,546/ML for dairying (ABS 2010a), this gives a gross potential benefit of $50M for the Tasmanian industry. It is however unrealistic to assume 100 % adoption of such a practice. However even at an adoption rate of 5 % this would equate to a potential benefit of $2.5M to the industry. Therefore in economic terms, 1 ML/ha represents a considerable saving by farmers. Furthermore, the increased labour input required to schedule deficit irrigation according to a rainfall deficit is minimal, so it is realistic to suggest that farmers could achieve these dollar savings.

In terms of irrigation demand, the MIWUI is a more useful index which takes into account the rainfall contribution to DM production. Where summer rainfall is minimal and the GPWUI of dryland production is comparatively low, irrigation water can value add to rainfall inputs, increasing the MIWUI. In the case of treatments I3 and I4, the GPWUI was lower than the dryland value, and therefore the MIWUI was comparatively lower (Table 3.4). The opposite was true of the other irrigated treatments, particularly I2 and I7 which recorded the highest MIWUI values of 1.59 and 1.63 t DM/ML, respectively (Table 3.4). A modelling simulation study taking into account variation in 40 years of climatic data suggested that the MIWUI could be increased to above 2 t DM/ML across dairying regions in Tasmania (Rawnsley *et al.* 2009). This therefore suggests that there is still opportunity to increase the GPWUI by improving irrigation and agronomic management practises.

3.5 Conclusion

The aim of the current study was to determine whether there was a DM yield penalty in increasing the soil water deficit, to improve the potential for capturing intermittent rainfall events, and thus save water. Whilst this study didn't specifically quantify whether deep drainage was reduced through practising deficit irrigation, nor whether leaf level WUE was increased, it has determined that there is the potential to reduce irrigation inputs without having a negative effect on herbage DM yield or forage nutritive value through adopting a deficit irrigation strategy. However, the current study was conducted over a contracted period of the irrigation season and was only run for one year. Therefore further assessment of the concept over multiple years, soil types and environments is recommended, in order to assess average water savings that may be possible through this approach.

Chapter 4: Opportunities and limitations to improving the irrigation response of perennial ryegrass under field conditions

4.1 Introduction

Irrigation water is becoming increasingly limited in Australia, with environmental concerns, climate change and demands from other sectors of the community reducing the supply of water for irrigation and/or increasing its cost. As a result, water use efficiency (WUE) of pasture production has become an important performance indicator of sustainable forage production in pastoral industries. Water use efficiency is broadly defined as the ratio of a given level of physical product (output) to a given level of consumed water (input) (Purcell & Currey 2003). At the leaf level, WUE is commonly discussed in terms of either instantaneous measurement of the efficiency of carbon gain per water loss (hereby referred to as leaf WUE, denoted WUE_l) or as the integral of such efficiency over time, expressed as the ratio of biomass accumulation to water transpired (referred to as transpiration efficiency; Jensen 2007; or biomass water productivity; Steduto *et al.* 2007). Methodologies to calculate components of the water balance (inputs and outputs) to determine transpiration water use are available but can be difficult to measure directly (Evett *et al.* 1995; Tolk *et al.* 1995; Ward *et al.* 1998). Thus for broad application of on-farm irrigation management, water use indices based on forage yield per unit of irrigation applied (t DM/ML) are often used to benchmark irrigation performance (generally referred to as irrigation efficiency and expressed as the irrigation water use index; IWUI).

The theoretical potential of perennial ryegrass to augment WUE_l without negatively impacting on DM yield was tested in Chapter 2. A two-fold increase in WUE_l was attained with no significant impact to biomass accumulation. This was achieved through reducing non-beneficial transpiration during daylight hours when evaporative demand was greatest, and a nightly watering regime to ensure leaf hydration so that carbon fixed could be utilised in growth.

At the field level, regulating plant water use has been achieved in a number of crops through adoption of irrigation practices such as deficit irrigation (Costa *et al.* 2007; Fereres & Soriano 2007). On a small-scale plot trial the potential of deficit irrigation to improve WUE of pasture yield (IWUI) was demonstrated in Chapter 3. Over the experimental period a 50%

reduction in water applied was achieved without penalty to DM yield or herbage nutritional value. However, the additional variability introduced by grazing cows pertinent to a dairy pastoral setting, and the inherent spatial variability of soil characteristics and irrigation application on a paddock scale, has the potential to limit improvements to WUE_I achieved through irrigation scheduling (Fereres & Soriano 2007; Greenwood *et al.* 2010; Rodrigues & Pereira 2009), which has not yet been adequately tested under grazed conditions subject to deficit irrigation.

In the practice of deficit irrigation, less water is applied than is needed to meet full losses of water from ET, thus creating a soil water deficit and exposing plants to mild water stress. Without careful scheduling of irrigation which consists of determining the amount and the timing of irrigation applications, plants may inadvertently be exposed to higher stress levels than desired. There are two main methods to schedule irrigation: 1) by replacing crop ET according to a soil water balance or, 2) by triggering irrigation according to the soil water status at defined depletion levels. The first method requires the use of a weather station to estimate daily evapotranspiration (ET), commonly calculated using the FAO-56 Penman-Monteith combination equation (Allen *et al.* 1998), and a spreadsheet to track inputs (rainfall and irrigation) and outputs (ET, drainage and runoff). The second method consists of monitoring soil water status either by direct gravimetric sampling or using soil moisture sensors.

The advantage of soil water monitoring is that in combination with precision irrigation techniques, spatial and temporal variability in water use can be accounted for through applying water variably across a given area according to demand (Krum *et al.* 2010; Sadler *et al.* 2002). When coupled with wireless technology and a decision support system, soil water monitoring allows the potential for real-time adjustment of irrigation decisions (e.g. Holloway-Phillips *et al.* 2008; Kim *et al.* 2008; Vellidis *et al.* 2008). By the same virtue, adequate surveying of spatial variability in soil hydraulic characteristics is required, as well as an understanding of the impact of soil variation on DM yield, for soil moisture sensors to provide greater accuracy than an ET-based estimate of water use, which is applied across a whole farm (McCready *et al.* 2009). Furthermore, the cost and performance of sensors varies greatly, and require correct installation, calibration and placement within the soil profile for readings to be reliable (Greenwood *et al.* 2010). Therefore in some situations, investment in soil moisture monitoring may not be justified (DeJonge *et al.* 2007).

The aim of the current study was to determine if the use of granular matrix sensors (GMS) for direct assessment of soil water demand across a paddock, improved the regulation of water use by plants and therefore the DM response to water applied. In addition, a deficit irrigation schedule was included to assess the production risk associated with scheduling irrigation closer to the plant stress thresholds in a variable soil water setting. Granular matrix sensors, which measure soil water potential (Ψ_{soil}, unit KPa) were chosen because of their relatively cheap cost compared to other sensors such as capacitance-based technologies (Greenwood *et al.* 2010), and as such have a greater potential for commercial adoption. Through continual monitoring of Ψ_{soil} and pasture growth, an additional aim was to determine if Ψ_{soil} was a good predictor of DM consumed by grazing cows for use in precision irrigation management.

4.2 Materials and methods

4.2.1 Site and soil description

The field study was conducted at the Tasmanian Institute of Agricultural Research, Dairy Research Facility on the north-west coast of Tasmania, Australia (41.08°S, 145.77'E; elevation 155.0 m) between December 2009 and April 2010. The 2.0 ha experimental site was an established perennial ryegrass (*Lolium perenne* L.) dominant pasture, on deep clay loam Ferrosol soil (Red Mesotrophic Haplic Ferrosol; Isbell 1996). Analysis of the soil profile to a depth of 7.5 cm before the study commenced indicated mineral concentrations of 19.9 mg P/kg (Olsen P test), 195 mg K/kg (Colwell K test), and 15.9 mg S/kg (potassium chloride extracted S), as well as a pH (H_2O) 6.3, and electrical conductivity 0.096 dS/m. Following soil test results, the experimental site was fertilised with triple superphosphate (21 % P, 1 % S), muriate of potash (50 % K) and single superphosphate (9 % P, 12 % S) at a rate equating to 50 kg P/ha, 50 kg K/ha and 20 kg S/ha to ensure that nutrients were non-limiting to pasture production. Applications of N fertiliser were applied at a rate of 46 kg N/ha as urea (46 % N) after each grazing.

Weather data were collected from the Australian Bureau of Meteorology weather station on the site, and Table 4.1 presents total rainfall, and mean maximum and minimum daily temperatures for each month of the experimental period. Daily potential evapotranspiration (PET) was calculated according to the FAO-56 Penman-Monteith combination equation (Allen *et al.* 1998) using data from a Davis-Vantage Pro2^{TM} (Davis Instruments Corp., Hayward, CA) automatic weather station, also located on site. The climate for this region is considered temperate maritime with a winter dominant rainfall pattern. The rainfall over the experimental period (December-April) was similar to the long-term average (1960-2009) rainfall of 269 mm for the same period.

Table 4.1 Total monthly rainfall (mm) and mean daily minimum and maximum temperature (°C) for each month of the experimental period (December 2009 to April 2010).

Month	Total rainfall	Temperature (Max.)	Temperature (Min.)
December[A]	20.7	20.3	9.5
January	5.8	21.5	10.3
February	64.6	22.5	13.0
March	98.2	20.6	10.7
April[B]	45.8	16.9	9.9

[A]Calculation period for the month December starts from 13th

[B]Calculation period for the month of April ends on 16th

4.2.2 Experimental design

The experimental design consisted of 4 spray-irrigated treatments arranged as a randomised block design with 3 plot replicates. Each treatment consisted of 4 K-line pods spaced 10 m apart, with controlled pressure at the inlet of each line maintained at 137.9 kPa by a Nelson™ high-flow pressure-limiting device. The pods were arranged so that flow rate reduced outwards from the centre at the same rate along the length of the line. This resulted in an average delivery rate of 3.69 mm/hr, with a distribution uniformity (DU) of 70 % at 1.5 m from the centre line (hereby referred to as zone A), and an average delivery rate of 3.1 mm/hr and DU 73 %, 4.5 m from the centre line (hereby referred to as zone B). The uniformity of water distribution was measured by placing catch cans every 2 m by 1.5 m in a grid of total dimensions 10 m by 6 m, either side of the irrigation centre line. Distribution uniformity was then calculated as the ratio among the average applied depths collected in catch cans in the lower quarter to the total average irrigation depths, expressed in mm. This was assessed four times during the experimental period under a range of wind conditions. Irrigation applications times were calculated according to the average application rate in zone A.

Irrigation was scheduled using either a rainfall deficit water-balance approach (unit mm) or *in situ* monitored soil water potential (Ψ_{soil}; unit KPa), with irrigation applied at two equivalent irrigation trigger points – 1) well-watered: 20 mm rainfall deficit ≈ -30 KPa, and 2) deficit: 60 mm rainfall deficit ≈ -75 KPa. The rainfall deficit was calculated as the difference in accumulated PET minus rainfall. Any watering event that increased the deficit above zero was classed as zero and not a positive value in the water balance sheet, as this additional water was assumed to be lost as drainage below the root-zone.

The equivalent Ψ_{soil} was determined by averaging all sensors within respective well-watered and deficit treatments when the target rainfall deficit had been reached for the first time. This removed the problem of sensor placement within the root-zone (Blonquist *et al.* 2006) and estimating soil KPa from soil moisture retention curves. Soil water potential was measured using granular matrix sensors (Watermark^{TM} soil water sensors, Irrometer Co., Riverside, CA) installed 0.3 m below the soil surface where the majority of the roots-zone ends (Chapter 3). Six sensors were installed on either side of the K-line centre; 3 located in zone A and 3 in zone B. Watermark sensors were read daily with a Hansen AM400 Soil Moisture Data Logger with Graphic Display (M.K. Hansen Co., East Wenatchee, WA). For irrigation scheduling purposes, only readings from sensors in zone A were used (total of 9 sensors per treatment). The spatial variation between replicates of a treatment in zone A recorded for the irrigation trigger point over time, was calculated as the coefficient of variation (%) (standard deviation/mean *x* 100).

Once an irrigation trigger point had been met, either 20 mm or 40 mm of irrigation was applied to the respective well-watered and deficit irrigation treatments. The four irrigation treatment combinations of scheduling method and application amount are hereby referred to as *Evap*1 (20mm-20mm), *Sens*1 (-30KPa-20mm), *Evap*2 (60mm-40mm) and *Sens*2 (-75KPa-40mm).

A rainfall deficit of 20 mm represents 50 % of the plant available water for this soil type and is the current industry recommendation for maximising DM yields. Therefore both *Evap*1 and *Sens1* represent a well-watered irrigation management practices whereas treatments *Evap2* and *Sens2* are considered deficit irrigation practises as they had the potential to expose plants to soil water stress. A rainfall deficit of 60 mm was chosen, as previous work (Chapter 3) had demonstrated that the level of exposure to water stress was not sufficient to have a negative impact on DM yield.

4.2.3 Dry matter consumed

The experimental area was grazed by 78 Holstein Friesian heifers at a grazing interval coinciding with emergence of 2.5-3.0 elongated ryegrass leaves/tiller (Fulkerson & Donaghy 2001) of the well-watered treatments. Where the pasture biomass on offer was calculated as exceeding 2 days of feed requirements for the herd, the experimental period was grazed by block using temporary fencing. A pre-experimental grazing was completed on 7 December, and a total of 4 grazings (3-9 January, 4-8 February, 10-17 March and 16-21 April) were undertaken.

Pre- and post-grazing herbage DM measurements were made at each grazing event using a calibrated rising plate meter (Earle & McGowan 1979). A total of 60 rising plate meter height measurements were taken for each zone (30 each side of the centre line) per plot, and the difference between the pre- and post- grazing measurements was take as the amount of pasture DM consumed from each treatment. Before each grazing, 40 calibration quadrats (0.25 m^2) were sampled at random across all treatments and cut to a height of 5 cm with hand shears taking one raising plate meter measurement within the quadrat before and after cutting. The cut herbage was collected and dried at 80°C for 48 h and resulting dry herbage material regressed against the plate meter reading (difference before and after equates to the herbage removed when cut), for conversion of plate meter height to consumed DM.

4.2.4 Water use efficiency

Water use efficiency at the canopy level was reported as the irrigation water use index (IWUI), calculated as total DM yield/irrigation water applied (Purcell & Currey 2003). Compared to Chapter 3, DM yield was taken as that consumed by the cow, as opposed to total grown (herbage ≥5 cm). At the leaf level, WUE_l was calculated according to the ratio of assimilation to stomatal conductance. Leaves were measured 5 times during the experiment (29 Dec., 1 Jan., 24-25 Feb. and 3 March), sampling at random within a 0.3 m radius of a soil moisture sensor across a range of soil hydration levels on each measurement day. This was more practical than sampling regularly across treatments due to the requirement for cloudless conditions and the restricted time period (11am-2pm) in which to measure leaves. Measurement of gas exchange parameters including assimilation, transpiration and stomatal conductance were made using a portable gas analyser (Li-6400; Licor, Lincoln, NE, USA), with a light intensity of 1500 μmol quanta m^{-1} s^{-1} at ambient temperature and vapour pressure deficit of 1.5 KPa. Three youngest fully expanded leaves (YFEL) exposed to full sunlight were sampled intact, per measurement. Adjacent to these leaves, an additional 3 YFEL were excised at the leaf base and wrapped immediately in plastic wrap, bagged and placed in a cooled sealed container for later determination of leaf water potential (Ψ_{leaf}) using a Scholander pressure bomb (Model 615, PMS Instrument Company, Albany, OR, USA).

4.2.5 Statistical analysis

Dry matter yield variables and WUE indices were analysed using ANOVA procedures within proc mixed from the SAS statistical package, version 9.1 (SAS Institute Inc., Cary, NC, USA), with plot replicates fixed as a random effect. The effect of the irrigation management practice (4 treatments) on DM yield was analysed for each zone (A and B) separately. The risk associated with irrigation application efficiency was assessed according to the change in DM yield of zone B to zone A for each treatment. The overall effect of the irrigation practice (scheduling method and trigger points) and application efficiency was evaluated by averaging the total DM yield between zones for each treatment. Where a significant effect was detected, Tukey-Kramer (Kramer 1956) was used for pairwise comparisons and significance reported when $P<0.05$.

The DM consumption of each treatment replicate per zone averaged over the 4 harvests (4 treatments by 2 zones by 3 reps) was regressed with the corresponding average soil water potential value observed at the triggering of an irrigation event, performed using proc reg. The Ψ_{soil} minimum for each treatment was averaged across all replicates for each zone (4 treatments by 2 zones) and presented with standard deviation.

A linear regression was fitted to the relationship between midday Ψ_{leaf} and Ψ_{soil}. To improve the visualisation of the trend, Ψ_{leaf} was pooled according to the average Ψ_{soil} ranges experienced by the different irrigation treatments including -20 to -40 KPa, -40 to -60 KPa, -60 to -80 KPa and -80 to -110 KPa, and standard error bars calculated for each variable.

To determine whether direct measures of spatial variation in water use improved the average growth response to applied irrigation water, the IWUI was analysed separately for each zone and as an interaction (zone by treatment). Significant differences between treatments for IWUI differentiated according to the scheduling method (Ψ_{soil} *"sens"* versus rainfall deficit *"Evap"* treatments) when analysed as an interaction, which was further described according to linear regressions between applied irrigation water and least squares means of DM yield. A polynomial function with a zero intercept was applied to the relationship between midday Ψ_{leaf} and WUE_l using proc nlin procedure. The coefficient of determination (R^2) was used to indicate the level of variance explained by the model and was expressed as $R^2 = 1 - SS_{error} / SS_{total}$, where SS_{error}= residual sum of squares and SS_{total} = corrected total sum of squares.

Unless otherwise stated, a significance level of 5 % was used throughout. Figures were produced in Sigmaplot (SPSS Inc. Chicago, IL, USA).

4.3 Results

4.3.1 Soil water availability

The scheduling of irrigation by both a rainfall deficit and Ψ_{soil} at two equivalent soil water depletion levels resulted in differences in the total amount of water applied between treatments, and consequently on soil water availability over the experimental period (Fig. 4.1a and 4.1b). In each treatment, the average Ψ_{soil} observed at a trigger point was greater in zone A than zone B, consistent with a 16 % lower irrigation rate in zone B than in zone A (Table 4.2). The scheduling of irrigation events according to soil sensors was effective in maintaining plants within the desired soil water range of -10 to -30 KPa (*Sens*1) and -10 to -70 KPa (*Sens*2), with the average minimum soil water tension observed in zone A ranging over time by 6 KPa (*Sens*1) and 17 KPa (*Sens*2), compared with 23 KPa (*Evap*1) and 43 KPa (*Evap*2) where irrigation was scheduled according to a rainfall deficit.

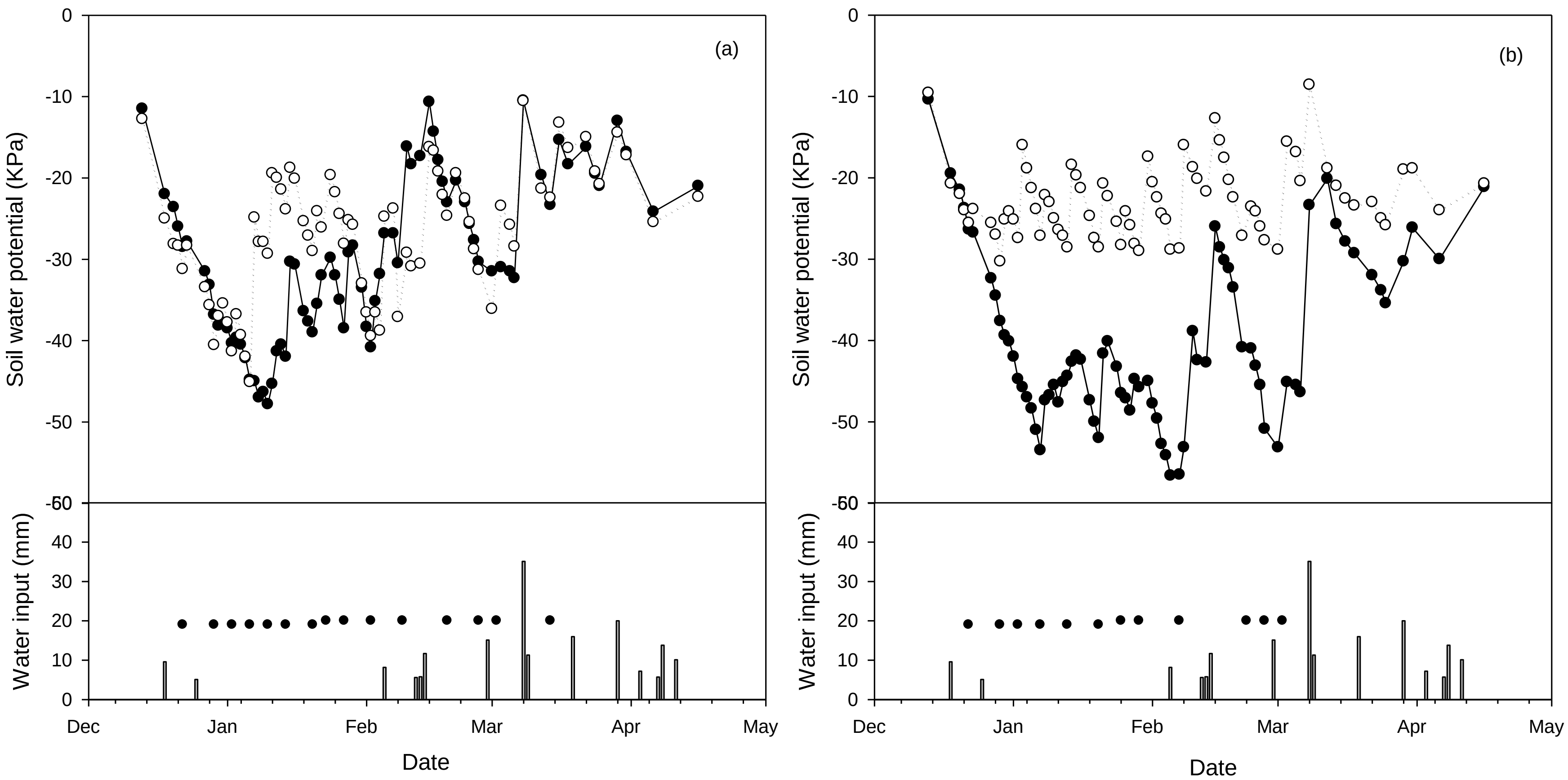


Figure 4.1a The top panel shows the progression of soil water potential (KPa) measured at 0.3 m below the soil surface over the duration of the experimental period. Each data point is an average of 9 sensors (3 sensors per 3 reps) for each of the four irrigation treatments – *Evap*1 (a) and *Sens*1 (b), per zone – A (open circles) and B (closed circles). For visualising the soil water potential differences between zones standard errors were omitted. On the bottom panel, bars represent rainfall events ≥5 mm, and closed circles irrigation events.

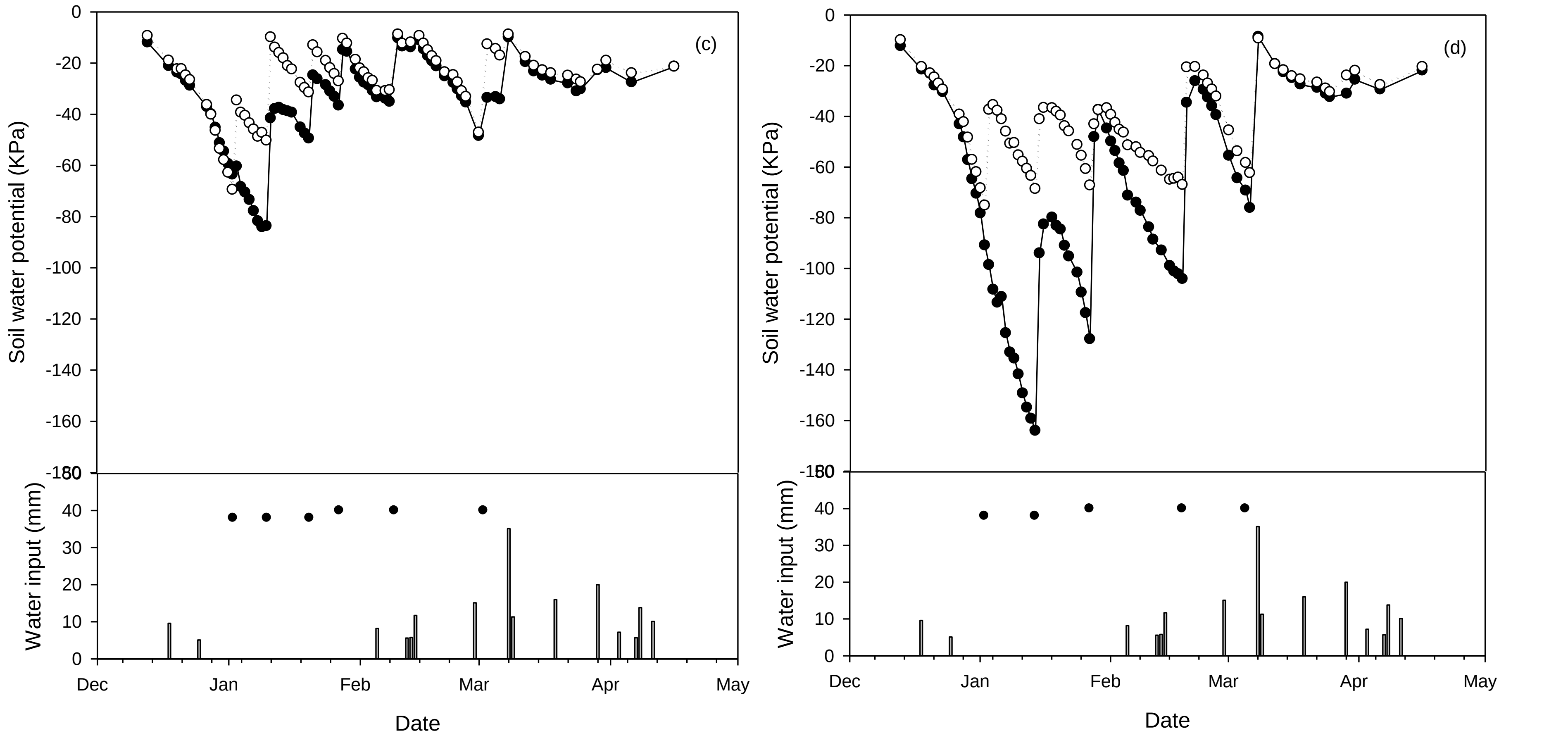


Figure 4.1b The top panel shows the progression of soil water potential (KPa) measured at 0.3 m below the soil surface over the duration of the experimental period. Each data point is an average of 9 sensors (3 sensors per 3 reps) for each of the four irrigation treatments – *Evap*2 (c) and *Sens*2 (d), per zone – A (open circles) and B (closed circles). For visualising the soil water potential differences between zones standard errors were omitted. On the bottom panel, bars represent rainfall events ≥5 mm, and closed circles irrigation events.

Table 4.2 Soil water potential (Ψ_{soil}; -KPa) measured at the time of an irrigation event for each zone A and B, averaged across the experimental period (Dec. 13th-April 16th) and reps of each irrigation treatment, with standard errors given in parentheses; total irrigation applied (mm) for each zone; total average yield of both zones and individually (t DM/ha); percentage change in yield between zone A and B (%); and the irrigation water use index (IWUI: yield/irrigation applied) (t DM/ML). Letters within columns indicate means which are significantly different at *P*=0.05.

Treat	Ave Ψ_{soil} (zone A)	Ave Ψ_{soil} (zone B)	Irrigation applied (zone A)	Irrigation applied (zone B)	Total ave. yield (A+B)	Yield (zone A)	Yield (zone B)	% change in yield between zones	IWUI
*Evap*1	32 (16)	35 (14)	293	246	4.41^{a}	4.91^{a}	3.90^{a}	20.48	1.63^{b}
*Sens*1	28 (3)	45 (27)	234	197	4.02^{ab}	4.32^{ab}	3.72^{ab}	19.08	1.87^{a}
*Evap*2	43 (22)	52 (19)	234	197	3.53^{bc}	3.91^{b}	3.15^{b}	13.99	1.64^{b}
*Sens*2	67 (20)	112 (55)	196	165	3.37^{c}	3.73^{b}	3.01^{b}	19.39	1.87^{a}
P-value					<0.01	0.01	0.01	0.66	<0.01
s.e.m.					0.32	0.16	0.21	4.47	0.08

A significant (P<0.001; r^2=0.31) linear relationship between Ψ_{soil} and midday Ψ_{leaf} was observed (Fig. 4.2) indicating that sensor readings provided an indication of average plant water status.

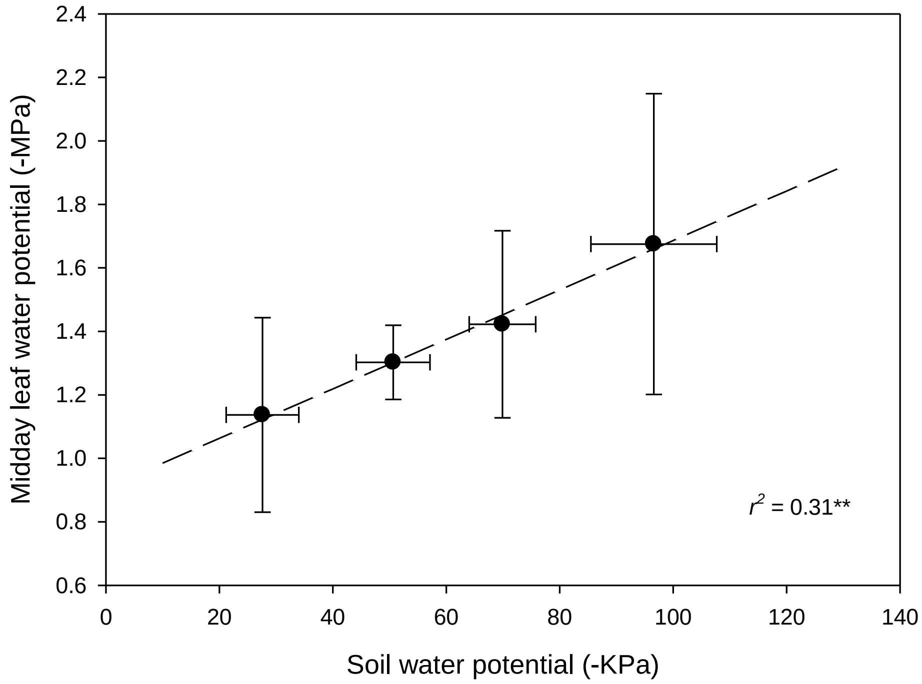


Figure 4.2 Plot of midday leaf water potential (-MPa) against soil water potential (Ψ_{soil} ,-KPa) sampled across treatments over 5 measurement days (29 Dec., 1 Jan., 24-25 Feb. and 3 March; n=52). Linear regression was significant (**, P<0.001), explaining 31% of the variability. Soil water potential was pooled according to the average Ψ_{soil} ranges experienced by the different irrigation treatments including -20-40 KPa, -40-60 KPa, -60-80 KPa and -80-110 KPa (average n=13). Bi-directional bars indicate standard errors for each variable.

4.3.2 *Water use efficiency*

The integrated effect of both improved timing and amount of irrigation application was an increase in the IWUI where plants were scheduled by soil sensors (Fig. 4.3). Whilst there was an irrigation treatment effect there was no zone effect or interaction.

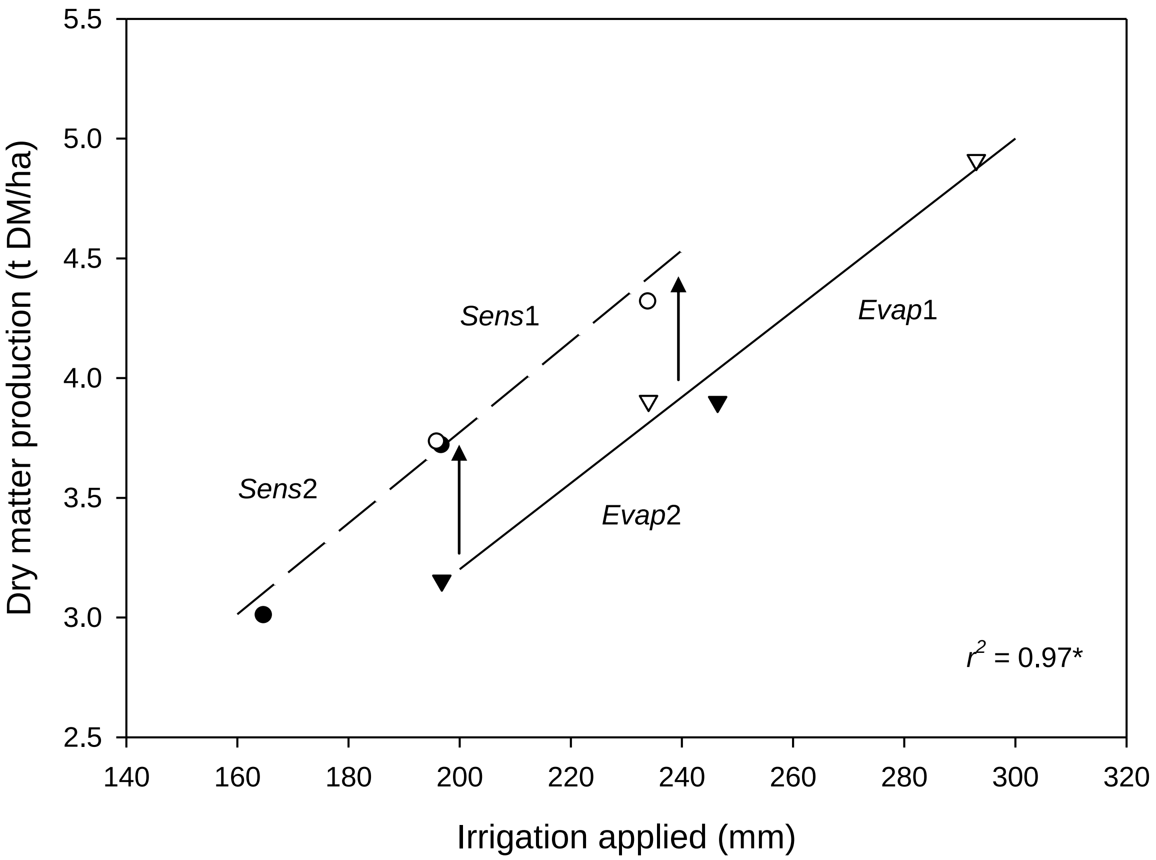


Figure 4.3 Linear relationships between the least square means of total dry matter consumed and irrigation applied averaged across 3 reps, for each of the two scheduling methods – soil moisture sensors (*Sens*1: open circles and *Sens*2: closed circles) and rainfall deficit (*Evap*1: open triangles and *Evap*2: closed triangles). The coefficient of determination (r^2), which was the same for each regression, and significance (*, $P<0.01$) is provided. The dry matter response to irrigation inputs is denoted by the slope of the regression which for "*Sens*" treatments was 1.9 t DM/ML and for "*Evap*" treatments was 1.8 t DM/ML.

Leaf-level responses to internal water status were consistent with the relationship found for plants grown under glasshouse conditions, with WUE_l increasing curvilinearly with decreasing midday Ψ_{leaf} (Fig. 4.4).

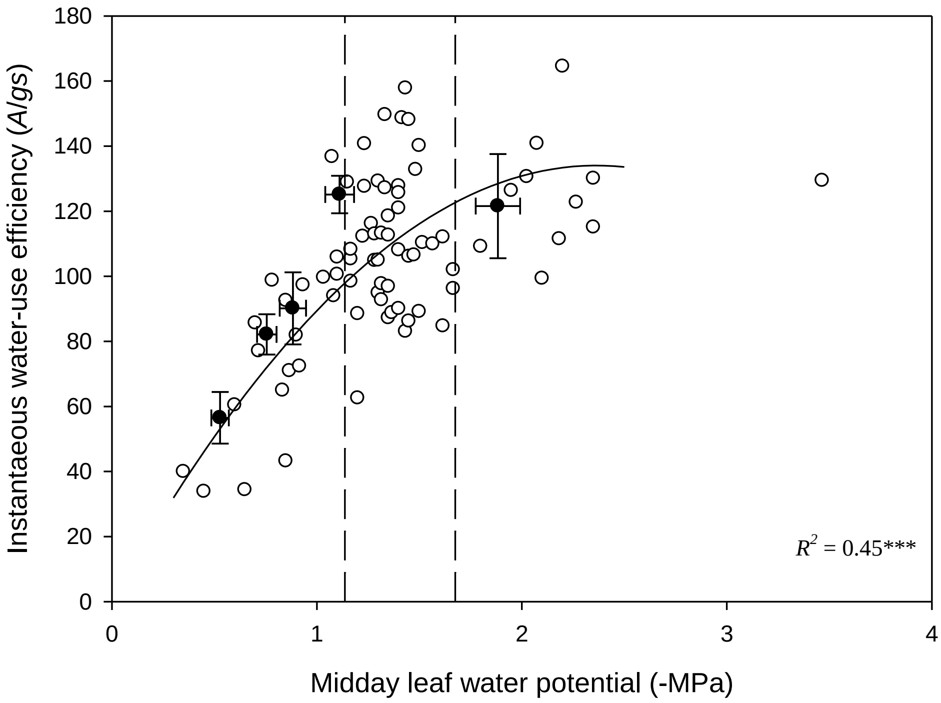


Figure 4.4 Instantaneous water use efficiency (WUE_l) measured by the ratio of assimilation to stomatal conductance (*A/gs*) as a function of midday leaf water potential (Ψ_{MD}; -MPa). A polynomial function was applied to the experimental field data (open circles) and the estimated coefficient of determination calculated as 0.45, which was significant at $P<0.001$ (***). Vertical dashed-lines indicate the average range in Ψ_{MD} observed in the field. For comparison, WUE_l data from Chapter 2 of plants grown under glasshouse conditions at different soil water availabilities is provided with bi-directional bars indicating standard errors for each variable (closed circles).

When Ψ_{leaf} was pooled according to the range in Ψ_{soil} experienced by each treatment, the average Ψ_{leaf} for field plants ranged from -1.1 to -1.6 MPa (Fig. 4.2), compared with -0.5 to -1.9 MPa across the glasshouse treatments (Chapter 2). For well-watered plants out in the field experiencing a Ψ_{soil} range between -20 to -40 KPa (Table 4.2), the estimated Ψ_{leaf} was -1.1 MPa (Fig. 4.2). This compares to the glasshouse grown plants where the most hydrated treatment was designed to maintain field capacity conditions (-10 KPa), which was reflected in a much lower Ψ_{leaf} of -0.5 MPa and hence also WUE_l (Fig. 4.4).

4.3.3 Water use and dry matter consumption

In general the less total water that was applied over the experimental period, the greater the average Ψ_{soil} recorded at an irrigation trigger point (Table 4.2). As a predictor of DM consumed, the Ψ_{soil} at the trigger point explained 43 % of the variation in DM yields across treatment replicates (Fig. 4.5).

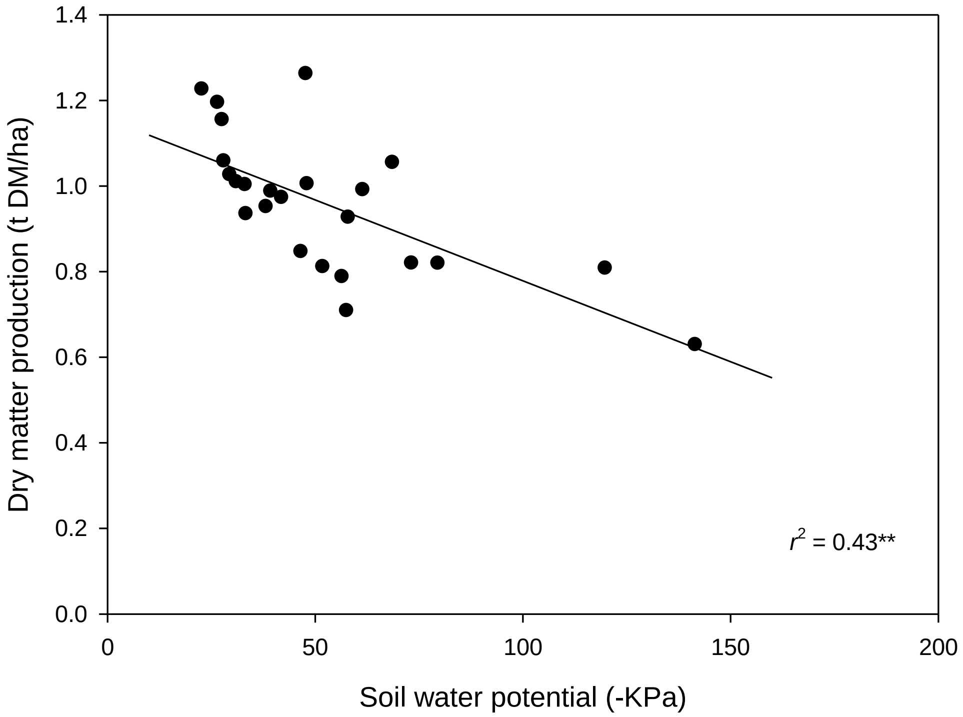


Figure 4.5 Dry matter consumed by the cows (t DM/ha) for each individual treatment rep and zone of 4 harvests, regressed against the average soil water potential (-KPa) of 3 sensors at the time of an irrigation event over the same period. A linear relationship was fitted to the data, with the coefficient of determination (r^2) shown at a significance level of P<0.001 (**).

The least total amount of water was applied in *Sens*2 (196 mm) over a 73 day irrigation period which was 33 % below the highest total irrigation input for *Evap*1 of 293 mm applied over 82 days. The resulting yield of *Sens*2 irrigation treatment was significantly lower than *Evap*1 in both zones (Table 4.2). Despite *Evap*2 having an irrigation interval of ~40 mm, the equivalent amount of total water was applied in *Sens*1, which triggered at an average of -28 KPa (Table 4.2). However the average trigger point Ψ_{soil} of *Evap*2 was 15 KPa less than *Sens*1 owing to the fact that the average irrigation interval was 9 days compared with 5 days. There was no significant difference in DM consumption between *Sens*1 and *Evap*2 despite the difference in the Ψ_{soil} observed at a trigger point. Dry matter consumption of the irrigation treatments *Sens*1 and *Evap*2 was also not significantly different from treatment *Sens*2. In comparison, treatment *Evap*1 was consistently different from *Evap*2 and *Sens*2 in both zones (Table 4.2).

Despite the fact that the magnitude of the Ψ_{soil} difference between zones varied between treatments, the percentage reduction in DM yield of zone B compared with zone A was not significantly different between treatments (Table 4.2). Furthermore, considering that the overall spatial variation in Ψ_{soil} at the trigger point across 3 replicates per treatment ranged from 3.4-41.6% in zone A (data not shown), there was still linearity in the relationship between total DM yield and irrigation applied (Fig. 4.3). When the total yields of zones A and B were averaged for each treatment, the difference between treatments became more obvious, with the *Sens*2 treatment yielding 1.04 t DM/ha less than the *Evap*1 treatment (Table 4.2).

4.4 Discussion

The purpose of irrigating crops is to supplement shortfalls in water provided by rainfall in order to obtain optimum yield and quality (Howell 1996). Irrigation scheduling provides a means to maximise the use of water inputs (rainfall and irrigation) through both the timing and amount of irrigation water applied, with the aim to avoid soil water levels reaching the stage where plant water stress causes reductions in WUE through plant stress or death, and to minimise the losses of soil water below the root-zone or via runoff as a result of over-watering. However within the dairy industry alone, there is evidence to suggest that WUE under irrigation is highly variable (Armstrong *et al*. 2000), as are the irrigation scheduling practises adopted by farmers (Watson & Drysdale 2005), and therefore opportunity exists to increase water productivity through improved irrigation management.

Two strategies were tested in the current study to improve WUE. The first was to use soil moisture sensors to improve the prediction of water demand both spatially and temporally, and the second was to adopt a deficit-irrigation practice by increasing the soil water deficit at which irrigation was triggered. It was found that scheduling irrigation events by the use of Watermark^{TM} soil sensors (*Sens*1 and *Sens*2) improved the response of pasture to irrigation inputs by 0.24 t DM/ML, with a water-saving of 20-33 % compared with the current industry recommended practice (*Evap*1) (Table 4.2). Employing a deficit irrigation strategy resulted in a similar reduction in water applied. However in comparison, total yield was significantly reduced by 19.7 and 16.1 % under both the water-balance and soil sensor scheduling methods, respectively (Table 4.2). Under conditions where the distribution uniformity of irrigation application was low, there was no additional risk to DM yield from practising a deficit irrigation scheme, thus highlighting the potential of spatial variability in DM yield even where a water-maximising irrigation strategy is employed. The opportunities and limitations for improving WUE at the field scale are further discussed.

4.4.1 Deficit irrigation

In the practice of deficit irrigation, less water is applied than is needed to meet full losses from ET, thus creating a soil water deficit and exposing plants to mild water stress. Deficit irrigation has the potential to improve irrigation efficiency through either increasing rainfall utilisation and/or through reducing stomatal conductance, and the capacity to achieve this without negative impact on DM yield, depends on rainfall amount and distribution pattern (White 2007), and non-linearity in the relationship between assimilation and stomatal conductance (Fereres & Soriano 2007).

Under glasshouse conditions, a watering regime that restricted daily water use indicated that it was possible to augment WUE_l at the leaf level without significantly reducing DM yield, due to well-watered plants using water in excess of that required to maximise DM yield (Chapter 2). However one of the criticisms in translating pot-derived results to the field is that the rooting zone of potted plants is constricted, and consequently the soil drying rate tends to be more rapid than in the field and roots are unable to explore the soil profile for deeper water (Begg & Turner 1976; Jones *et al.* 1980). As a result, potted plants do not always have the same opportunity to acclimate to changing soil moisture conditions. However, close alignment of WUE_l in relation to midday Ψ_{leaf} was found between acclimated potted plants and field tested plants (Fig. 4.4), suggesting that well-managed pot experiments may be an acceptable means of testing the effects of moisture stress. Importantly, a curvilinear relationship between Ψ_{leaf} and WUE_l (Fig. 4.4) was observed in the field in further support of the understanding that water-deficit increases WUE at the leaf level up to a point beyond which further stress results in complete stomatal closure (Comstock 2002; Dingkuhn *et al.* 1989; Tambussi *et al.* 2007).

In Chapter 2 it was shown that only a small watering event under non-transpiring conditions was required to fully-hydrate leaves, despite the majority of the soil being substantially drier. By restricting the nightly watering amount, the time spent in the hydrated state was reduced, and thus also the unbeneficial use of water during daylight hours. A similar explanation may also be provided to the augmentation in the IWUI when irrigation was scheduled according to soil sensors (Table 4.2). In the field context, the use of soil sensors helped both maintain plants at the desired soil water deficit, particularly evident between *Sens*2 and *Evap*2, and regulate the amplitude in soil water availability experienced, as evidenced by *Sens*1 compared with *Evap*1 (Fig. 4.1b and 4.1a). It is by these mechanisms that the soil sensors are suggested to have helped regulate leaf level WUE. When the IWUI was analysed separately for each zone, the effect of the scheduling method was less obvious, which may suggest that the variation between reps was too large to differentiate treatment effects. However in biological terms the difference between the average IWUI between scheduling methods was still 0.2 t DM/ML of irrigation applied in zone A and 0.26 t DM/ML in zone B (data not shown).

The potential to augment leaf-level WUE in the field however may not be as significant as indicated in Chapter 2, as even under the well-watered irrigation strategy (*Sens*1 and *Evap*1), plants in the field were maintained within a Ψ_{soil} range of around -20 to -40 KPa in zone A (Fig. 4.1a), compared with the most hydrated treatment in the glasshouse trial which maintained the soil at field capacity (-10 KPa). As a result, Ψ_{leaf} was much higher in the glasshouse (-0.5 MPa) to that estimated from the linear regression of Ψ_{soil} and Ψ_{leaf} in the field (-1.1 MPa) (Fig. 4.2), and consequently field plants were on average operating at a higher WUE_l than well-watered glasshouse plants (Fig. 4.4).

This may explain why there was a general linear decline in DM consumed with irrigation inputs in the field (Fig. 4.5) and not the glasshouse (Chapter 2), which is consistent with the notion that the relationship between biomass production and water use is conservative (Steduto *et al.* 2007), as has been demonstrated in other pasture studies (Merot *et al.* 2008; Smeal *et al.* 2005). Thus limitations to improving WUE_l through irrigation management may be the constraint to DM yield. Therefore at the paddock scale, reducing water losses via runoff and deep drainage may be able to achieve greater water savings without the subsequent negative effects to yield (Hsiao *et al.* 2007).

Deep drainage was not explicitly measured in this study, and therefore rainfall utilisation cannot easily be quantified. However there were few occasions where sensors registered values above -10 KPa indicating saturation of the root-zone. This was particularly true of sensors in zone B (Fig 4.1a and 4.1b), although there was no significant zone effect on the IWUI to suggest an advantage to DM yield in the case that rainfall utilisation had increased in zone B (Table 4.2). Consequently, due to the reduction in irrigation rate from zone A to zone B, a DM yield decline was observed (Table 4.2).

Despite the fact that the minimum Ψ_{soil} observed in zone B ranged from -35 KPa in treatment *Evap*1 to as dry as -112 KPa in treatment *Sens*2 (data not shown), there was no significant difference in the DM yield reduction between zones A to zone B across treatments (Table 4.2). One of the risks associated with practising deficit irrigation is in order to achieve higher WUE plants tend to be regulated closer to the threshold where water deficits cause significant declines in production. Therefore under situations of high spatial variability or poor irrigation uniformity, deficit irrigated crops are more prone to yield variation in response to similar water inputs, i.e. variable WUE (Grove & Oosthuizen 2010). However for grasses, deviation from the linear response of DM yield to water appears to only occur when severe water stress causes leaf senescence. This was identified in Chapter 2 as coinciding with a midday Ψ_{leaf} of around -2 MPa. Thus the consistency in the DM yield reduction in zone B across treatments suggests the plant water stress level was not severe enough to cause dieback and therefore the reduction in DM remained in proportion to the reduction in water applied between zones (Table 4.2). In terms of absolute DM yield however, a soil water threshold of -75 KPa resulted in a significant reduction in yield compared to *Evap*1 and *Sens*1. Therefore for ensuring maximum yields, results from the current study recommend a -30 KPa threshold as measured at the base of the root-zone.

4.4.2 Precision irrigation with soil moisture sensors

Heterogeneity of soil physical characteristics (Sadler *et al.* 2002) and water application distribution (Jimenez *et al.* 2010) are key causes of spatial variation in crop performance. Soil moisture sensors have a particular advantage over meteorological based water use estimates in this respect, as they provide the opportunity to practice "precision irrigation", which aims to apply water only where, when and in the amount needed by the plant (Krum *et al.* 2010). Significant water-savings have been demonstrated from using soil sensors compared with time-based scheduling (e.g. Blonquist *et al.* 2006; Hedley & Yule 2009; McCready *et al.* 2009; Pathan *et al.* 2007; Qualls *et al.* 2001). The increase in WUE of 0.24 t DM/ML across both the well-watered (*Sens*1) and deficit irrigated (*Sens*2) treatments where sensors were used to schedule irrigation events, equated to a water-saving of 20 and 33 %, respectively, compared with the current industry recommended practice (*Evap*1) (Table 4.2). Furthermore, a significant regression between DM yield and the average Ψ_{soil} at the irrigation trigger point demonstrates the potential benefits of precision irrigation combined with the use of Watermark™ sensors (Fig. 4.5).

Soil matric potential measured by granular matrix sensors (GMS) reflects how tightly water is held within the soil and therefore is relative to the energy plants must expend to absorb water or the consequent plant water stress experienced by the plant. This is evidenced by strong correlation between Ψ_{leaf} and Ψ_{soil} (Intrigliolo & Castel 2004), and DM yield and Ψ_{soil} (Merot *et al.* 2008), though variation in the relationship was reportedly high. However, rather than just an indication of a sensor precision problem, variation in Ψ_{leaf} with Ψ_{soil} is likely to reflect the influence of evaporative demand on the rate of water flow through the plant and the corresponding hydraulic flow resistances between the bulk soil and the leaf tissue (Jones 2004). As it is the change in tissue water status that many aspects of the plant's physiology respond to, rather than bulk soil water content, dynamic changes in Ψ_{leaf} may partly explain the variation in DM yield not accounted for in the regression of DM yield to Ψ_{soil} (Fig. 4.5). As the soil dried out, variation in Ψ_{leaf} became particularly evident (Fig. 4.2), which is likely to reflect the non-linearity in the relationship between water content and water potential in both the soil and plant, which becomes exacerbated under dry soil conditions especially where there is high spatial heterogeneity in soil hydraulic properties.

However, there are limitations to the use of GMSs. They require good soil contact as they work by equilibrating with the surrounding soil moisture, so in coarse textured soil (i.e. sand) reduced soil/sensor contact may lead to incorrect estimation of soil water tension (Irmak & Haman 2001). In addition, GMSs tend to exhibit hysteretic behaviour (Thompson *et al.* 2006) and a high variability of readings (Intrigliolo & Castel 2004). However, when compared to the performance of other sensors based on Frequency or Time Domain Reflectrometry, GMSs were similarly able to describe general trends in soil moisture changes during the growing season (Leib *et al.* 2003), and are relatively cheap allowing the possibility to achieve higher spatial resolution through the use of multiple sensors. Over the 1 ha experimental area within zone A, the overall spatial variation in soil moisture at an irrigation trigger point across 3 replicates per treatment ranged from 3.4-41.6 % (data not shown). Thus applying precision techniques to account for variation at the scale assessed in the current study may not be viable when applied across a whole farm with multiple paddocks, soil types and terrains. Furthermore, as an irrigation scheduling tool, reliance on one sensor placed within a paddock is unlikely to be sufficient for achieving improved WUE. A study by Sadler *et al.* (2002) demonstrated the magnitude of variability that can exist within soil classification units, and over comparatively short distances, highlighting the need for improved identification of management zones and greater flexibility in the capacity to manage and apply irrigation at various rates in order to achieve optimum management (Evans & Sadler 2008; Green & Erskine 2004; Hedley & Yule 2009; Krum *et al.* 2010; Sonmez *et al.* 2008). However, of the few economic studies that evaluate precision irrigation, the general consensus is that it isn't feasible at current capital costs (DeJonge *et al.* 2007; Lu *et al.* 2005; Watkins *et al.* 2002).

4.5 Conclusion

This study demonstrated the potential use of soil granular matrix sensors to account for spatial and temporal variability in soil moisture across a paddock to improve the regulation of water use by plants and therefore the DM response to water applied. Further testing is required to improve the predictability of the relationship between DM yield and Ψ_{soil} if it is to be used with variable rate irrigation control. But through strategic placement of sensors to improve the average WUE of a paddock it is likely to be a useful irrigation tool. Considering that few farmers currently use any form of objective irrigation decision measures (ABS 2010b), as a first step, utilising a low-cost water-balance approach to increase rainfall capture is still likely to be an improvement on a set-scheduled irrigation strategy, which tends to dominate current practice (Watson & Drysdale 2005).

Chapter 5: The value of pre-season forecasts of irrigation requirements for optimising the scheduling practice

5.1 Introduction

Climate variability, particularly fluctuations in rainfall amount and distribution patterns, strongly influences production and profitability in agriculture. In Australia, rainfall variability has been well documented and is noteworthy for its strong variability compared to places with seemingly similar climates elsewhere in the world (Nicholls *et al.* 1997). As a result, the use of irrigation water has been an important practice to stabilise yields and increase total farm production and capacity (de Fraiture *et al.* 2010; Turral *et al.* 2010), and up until recently has been considered a reliable way to drought-proof farm production systems. However, persistent below-average rainfall for significant parts of southern and eastern Australia since 1996 (BOM 2011), has in recent years resulted in significant reductions in water allocated to irrigation (Sanders *et al.* 2010) and subsequent hikes in water prices during high demand periods (ABARE 2009). This has left irrigation-dependent farmers exposed to increased risk compared with dryland producers where drought preparedness has always been a necessity (Milne *et al.* 2008). The outcome from this experience has been an increased awareness to the importance of environmental flow needs and a push to improve water management and on-farm use, including the development of management options to help mitigate the risks associated with water restrictions.

Deficit irrigation is a scheduling strategy aimed at improving the allocation of limited water availability across the irrigation season, with the objective to avoid running out of water and exposing crops to excessive water stress. This is commonly achieved by restricting water inputs during particular drought-sensitive growth stages (regulated deficit irrigation) or through applying a proportion of crop water requirements at regular intervals (conventional deficit irrigation), and relying on increased rainfall capture to supply the remaining crop water needs. The benefits of deficit irrigation in achieving profitable returns under water-limited conditions has been demonstrated in a number of crops (refer to reviews by Geerts & Raes 2009 and Fereres & Soriano 2007). However the relative advantage of deficit irrigation in terms of the optimal soil water deficit to practice (in production or economic terms), is still dependent on rainfall variability and irrigation availability (Jalota *et al.* 2006; Rodrigues &

Pereira 2009; Sepaskhah *et al.* 2006). Furthermore, the purchase of additional irrigation water to meet production demand may not be the most profitable solution, and other management options such as reducing stock numbers (Griffith 2010; O'Reagain *et al.* 2009) and on-selling water shares (Khan *et al.* 2010b) may be more appropriate.

Model simulation is commonly employed to compare allocation strategies (and management strategies) in order to determine the practice that maximises yield and irrigation efficiency over a historical climate base (e.g. Bergez *et al.* 2001; Chen *et al.* 2010; Garcia-Vila *et al.* 2009; Pereira *et al.* 2003; Rawnsley *et al.* 2009). The restriction to this method is that the solution is generally definitive and therefore only provides guidance for the "best-bet" scenario. Improvements to exploratory modelling studies include where real-time optimisation models are integrated with crop-production models for intra-seasonal decision-making (e.g. Brown *et al.* 2010; Gowing & Ejieji 2001; Humphreys *et al.* 2008). However whilst optimisation may be directed to profits rather than just production, solutions are generally based on maximising returns on irrigation water applied. Therefore there is still a need for pre-season information to assess alternative management strategies where irrigation availability is below a profitable threshold.

Seasonal climate prediction offers the potential to anticipate variations in crop production early enough to allow adjustment of critical decisions. Forecasts of climate fluctuations with a seasonal (i.e. several months) lead-time are possible because the atmosphere responds to the more slowly varying ocean and land surfaces, an example being climate fluctuations associated with the El Nino-Southern Oscillation (ENSO) in the tropical Pacific (Troccoli 2010). The effects of ENSO on rainfall have been demonstrated to be significant particularly in the north and east of Australia, with the regions of influence shifting with the seasons (Goddard *et al.* 2001; Risbey *et al.* 2009; Vizard & Anderson 2009). Furthermore, high correlation between ENSO activity and agricultural production has been found for many other parts of the world (e.g. Ferreyra *et al.* 2001; Hansen *et al.* 1998; Meinke & Hammer 1997; Naylor *et al.* 2001; Phillips *et al.* 1998; Podesta *et al.* 1999; Potgieter *et al.* 2002; Selvaraju 2003).

There are two extreme phases of ENSO: a warm phase, "El Nino" events, which are often associated with severe droughts in Australia and elsewhere, and a cool phase, "La Nina" events; with time periods that do not fall within these extremes categorised as "neutral" (Potgieter *et al.* 2005). Indicators of ENSO activity include sea surface temperature and the

Southern Oscillation Index (SOI). The SOI is based on difference in air pressure anomalies between Darwin and Tahiti, which Stone and Auliciems (1992) subdivided into 5 Phases based on principle component analysis and cluster analysis of monthly SOI values, which reflect the importance of both magnitude and phase change on climate variability (Stone *et al.* 1996). Phases 1 (consistently negative) and 3 (rapidly falling) are commonly associated with El Nino; Phases 2 (consistently positive) and 4 (rapidly rising), La Nina; and Phase 5 with normal conditions.

A forecast is obtained by calculating probability distributions of cumulative rainfall for a period (or other variable to be predicted), by breaking up the historical record into subsets according to the SOI Phase in the lead month. This technique of 'stratified climatology' has been employed by the Queensland Government forecast system to provide 3-monthly rainfall outlooks (Fawcett & Stone 2010), and forms the basis of the predictive capacity of median dryland pasture growth provided by the "Aussie GRASS" service (Carter *et al.* 2000). Similar forecasting services are provided around the world. However despite the potential benefits of seasonal forecasts to reducing the risk associated with management decisions, adoption of this knowledge remains limited (Austen *et al.* 2002; Cobon *et al.* 2008; George *et al.* 2007; McCrea *et al.* 2005). There are a number reasons offered for why this might be the case which have been discussed in detail elsewhere (e.g. Ash *et al.* 2007). Notably, there is a need to develop more skilful forecasts with lead times more appropriate to key decision points in farm management, and with this, greater consultation with industry to ensure forecast relevance and successful uptake (Hammer 2000; Hansen 2002; Meinke & Stone 2005).

A cross-institutional effort to address the lack of information regarding water availability in the sugarcane industry exemplifies what can be achieved through industry engagement and the use of integrating forecast capacity into a crop modelling framework to improve confidence around irrigation schedules and productivity outcomes (Everingham *et al.* 2008). Briefly, the SOI Phase system was used to predict the likely water allocation based on historical annual streamflows for the Burnett River, which is a major source of water for sugarcane farmers in the Bundaberg region where the case study was undertaken. A biophysical model, "APSIM", was then used to simulate the projected yield and irrigation use under 10 different scheduling strategies with increasing plant-stress thresholds, in which total irrigation applied in a season could not exceed 4 ML/ha (farmer's nominal allocation). The greater the stress level, the longer it took to use the allocation. However, allowing too much stress to develop had the potential to under-utilise the allocation and have a detrimental effect on yield. Thus an optimised yield was dependent on the balance between short-term stress and longer-term (seasonal) water-availability. The irrigation applied each season to optimise yield was then expressed as the probability of exceeding the forecasted amount (expressed as a % of the nominal amount), for each of the 5 SOI Phases.

A similar approach is taken in the current study to forecast irrigation requirements and pasture yields for the irrigation season so that dairy farmers have information to determine whether irrigation allocations are sufficient to meet feed demands. "DairyMod", a mechanistic biophysical model developed for the Australian pastoral industry (Johnson *et al.* 2008), was used to simulate yield potential and irrigation requirements across 4 irrigation scheduling strategies using historical climate data from 1901 to 2008, for Elliott on the north-west coast of Tasmania. The scheduling strategies were designed to balance short-term stress with end-of-season stress (where the irrigation allocation has run out before the irrigation season has ended), by applying different proportions of cumulated potential evapotranspiration (PET) at regular intervals (100, 80, 60 and 50 % of a 20 mm PET deficit) (Rawnsley *et al.* 2009). Given a maximum irrigation availability (seasonal allocation), for each of the 5 SOI Phases, an optimised irrigation requirement and associated scheduling strategy is given as well as the modelled dry matter (DM) yield, so that further tactical decisions can be made if the predicted yield is likely to be insufficient to meet the feed requirements of the herd. Such tactical decisions might include buying in supplementary feed or culling poorly-producing cows.

The utility of this approach to irrigation decision-making is based on the assumption that seasonal water allocations can be planned, and that given the teleconnection between the SOI and rainfall variability (teleconnection = statistical relationships between climate anomalies; Goddard *et al.* 2001), that irrigation requirements are correlated with rainfall. Water management in irrigated catchments is currently quite conservative in Australia, with initial water allocation announcements at the beginning of the year generally based on the storage condition of reservoirs and lowest recorded inflows (1 in 100 years) to reservoirs. However, improved capacity to forecast future inflows using hydrological models and climate forecasts has demonstrated potential (Chiew *et al.* 2003; Khan *et al.* 2010b; Kirono *et al.* 2010).

The north-west region of Tasmania was chosen for the purpose of the current study, to investigate the value of irrigation forecasts in dairy production systems. To date, agricultural-based forecast studies have tended to be concentrated in the north-east of Australia where the SOI forecast system demonstrates strongest skill. Forecast *skill* is a term used to indicate the reliability of the system to provide a better indication of the coming season than simply relying on long-term climate records (Hayman *et al.* 2007). However in terms of assessing the *value* of a forecast system, Meinke and Stone (2005) highlight the need to distinguish between statistical skill and user impact, suggesting that even moderate forecast skill may have high value and agriculturally-significant impact under the right circumstances and if applied appropriately.

Dairying accounts of 19 % of water diversions for agricultural use (ABS 2006), and compared with other industries such as vegetable and fruit production, has a lower gross economic water use index ($/ML) (ABS 2010a). Whilst the effects of recent droughts have been less severe on the north-west of Tasmania compared to dairying regions on mainland Australia, the dairy industry nationally has come under increased pressure to improve irrigation efficiency. The temperate environment of Tasmania, with an average annual rainfall of 1200 mm, places dairy farmers in a good position to practice deficit irrigation and improve irrigation efficiency through increased rainfall harvesting. The aim of the current study was therefore to assess whether the SOI Phase forecast system had sufficient skill to improve knowledge of irrigation requirements compared with best-bet climatology, in order to optimise the choice of the irrigation scheduling practice as a means to improve irrigation efficiency and DM yield outcomes. The value of the forecast system was assessed in terms of water-savings and DM yield under both unrestricted and restricted irrigation allocation scenarios.

5.2 Methods

5.2.1 Crop model – DairyMod

5.2.1.1 Model simulation

DairyMod was used to model DM yield and irrigation water use at Elliott, north-west Tasmania (41.08°S, 145.77'E; elevation 155.0 m), over successive years and under four irrigation scheduling practices. Irrigation events were scheduled according to a rainfall deficit (cumulative PET - rainfall) of 20 mm, with different proportions of the rainfall deficit applied at each irrigation event, including a yield-maximising practice with a 20 mm application to refill the soil to field capacity (Practice 1), and 3 conventional deficit irrigation practices which applied 16 mm (Practice 2), 12 mm (Practice 3) and 10 mm (Practice 4) at each irrigation trigger point.

The model uses daily weather information and comprises soil water, soil nutrient, pasture growth and animal production modules. Daily climate data for Elliott was obtained from the Bureau of Meteorology SILO database (Jeffrey *et al.* 2001). Pasture was cut to a residual of 1.5 t DM/ha with successive defoliation events occurring when 3 leaves had fully expanded (to reflect best practice grazing management; Fulkerson & Donaghy 2001), for the period January 1901 to January 2009. Nitrogen was applied at a rate of 46 kg N/ha following defoliation or when the soil N status fell below a critical level of 10 ppm, to ensure that N was non-limiting. The model was initially run for a period of 40 years to ensure steady-state conditions within each module of DairyMod, and these conditions saved to form the base for all other simulations. Dry matter yield (net positive above-ground growth) was summed over the period October-April which represents the average irrigation season, and total irrigation inputs determined for the financial year (July-June).

The model has been previously evaluated by Cullen et al. (2008), with strong agreement between modelled and observed data for several pastoral systems in Australia and New Zealand under varying climatic conditions, and irrigated and rainfed situations. A deficit irrigation study undertaken at Elliott also demonstrated significant model accuracy (Rawnsley *et al.* 2009).

5.2.1.2 Model parameters

Parameterisation of the pasture growth and soil water modules was based on previous experimental work contained in Chapters 3 and 4, and in relevant literature. Information in

Cotching et al. (2002) was used to describe the soil physical properties of the dominant soil type on the north-west coast – red ferrosol. Important characteristics included relative water content at soil saturation, field capacity (-10 KPa), and wilting point (-1500 KPa) for determination of total plant available water. Soil physical dynamics were confirmed ($P < 0.001$, $r^2 = 0.63$) by comparing modelled data to observed soil water data from theta probes buried at 15 cm, collected from a representative field site at Elliott under dairy production in 2010, between the months May to July, inclusive. For the red ferrosol used in the current study, RAW is approximately 20 mm.

Leaf appearance rate was set as 9 days per leaf at 20°C and 17 days per leaf at 10°C, reflecting what has previously been observed in pasture growth studies undertaken on the north-west coast (Rawnsley *et al.* 2010). The restriction of growth under high temperatures was activated to occur above temperatures of 28°C, in line with temperature optimums for ryegrass growth (McKenzie *et al.* 2000; Mitchell 1953).

DairyMod has the capacity to scale the effect of dry soil regions on overall water uptake by a soil water compensation parameter, where ‘0’ results in no compensation of dry regions by wetter regions, and ‘1’ results in full compensation by wetter regions which effectively supply water until demand has been reached. To reflect the understanding that under gradients in soil water availability, root-to-shoot signals such as abscisic acid have been shown to limit plant water use (Davies & Zhang 1991; Dodd 2005), the compensation parameter was set to zero. The sensitivity of growth to water stress was further moderated via a growth limiting factor which is applied to both transpiration and photosynthetic processes according to the available soil water. According to findings in Chapter 3 the variation in leaf elongation rates even in well-watered treatments (I1 and I2) were substantial, and as such the water stress response was set to attenuate growth linearly between field capacity and wilting point.

Under water-stress, whilst the rate of senescence often increases due to drought-induced dieback (Chapter 2), the rate of tissue turnover from dead standing material to litter tends to be slower than in a well-watered sward, as a result of reduced soil moisture conditions for decomposition processes (e.g. Henry *et al.* 2008; Meentemeyer 1978). To simulate reduced rates of tissue turnover, the scaling factor for water stress effects on tissue flux was reduced to half of the well-watered rate.

5.2.2 Irrigation scheduling decision-making

The aim of the forecast system is to improve the accuracy in predicting irrigation requirements and DM yield under different irrigation allocations, so that further tactical decisions can be made. The usefulness of the system is evaluated by comparing the outputs where a fixed irrigation scheduling practice is followed (Fixed strategy) with one where the practices vary according to the SOI Phase forecast system (Forecast strategy). The step-process by which the scheduling practices under the Fixed and Forecast strategies are selected is as follows:

Step 1. Simulation output

DairyMod was used to obtain outputs of irrigation used and DM produced over 108 years of historical climate data (1901-2009) for each of the 4 irrigation practices (P1-P4).

Step 2. Optimising the practice for each year – "Perfect knowledge"

Comparing output for each year, the Practice that maximises yield (within 1 t DM/ha from the maximum value observed between the 4 practices) with the least amount of water is considered the optimised choice. Where there is "perfect knowledge", the optimised practice (and associated irrigation requirement) is chosen for each year. Therefore perfect knowledge represents the theoretical maximum achievement of any predictive forecast system using the 4 practices under the simulated environmental conditions.

Step 3. Selecting the most frequently observed practice – "Fixed strategy"

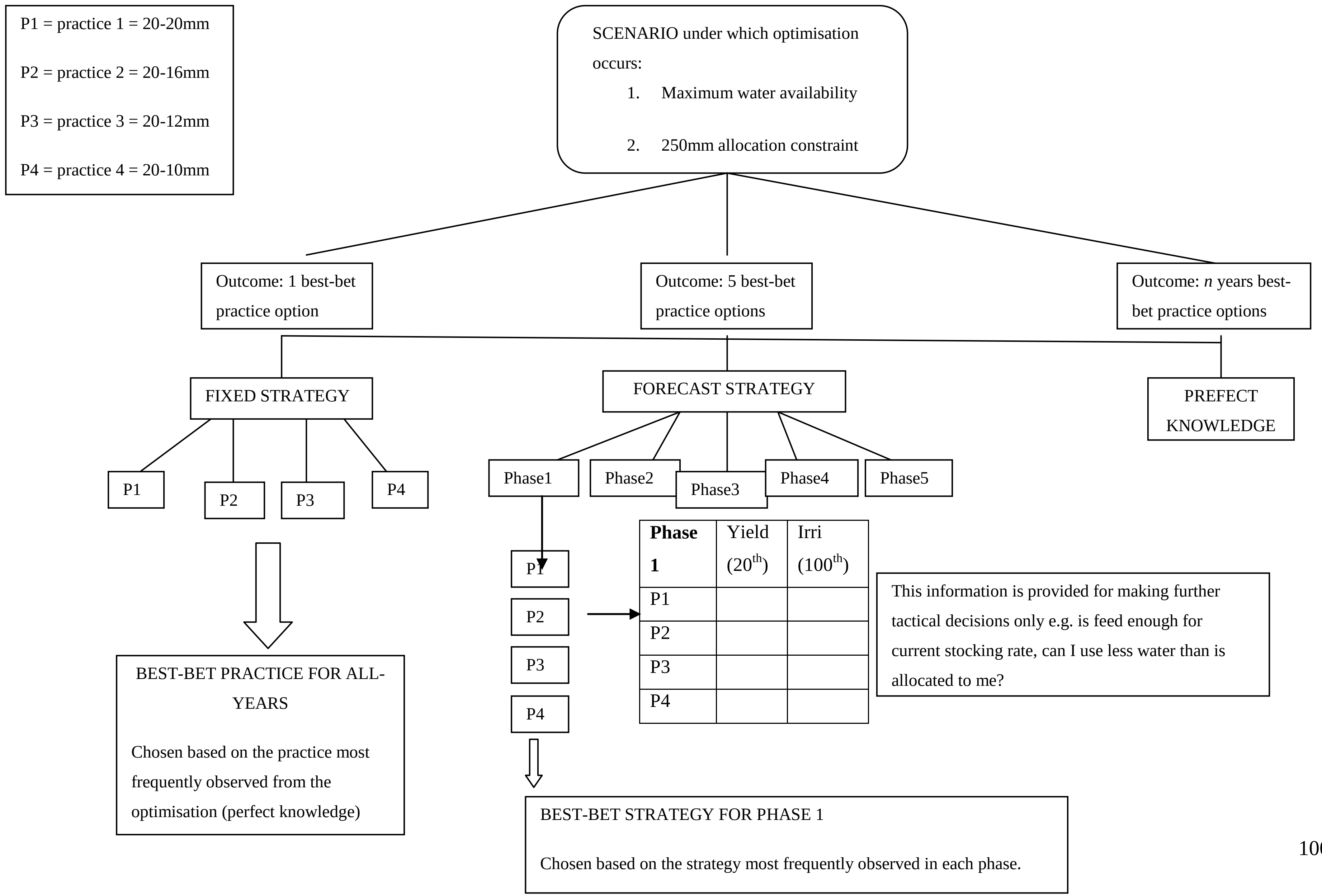
The extreme of perfect knowledge is where only 1 practice and irrigation requirement can be used each year. This equates to a "Fixed" strategy, and has been defined according to the most frequently observed practice in the 108 year optimised data. The Fixed irrigation requirement is the maximum irrigation amount observed for that practice in any one year.

Step 4. Selecting the practice for each SOI Phase – "Forecast strategy"

For the Forecast system, the 108 year optimised data is stratified according to the 5 SOI Phases in September-October. This gives little lead time with a November start to the irrigation season, however from preliminary work, provides the greatest forecast potential. The most frequent scheduling practice observed in each of the Phases is then selected as the best-bet phase strategy, and the irrigation requirement taken as the maximum observed for that practice. If the frequency is the same between practices, then the practice that maximises yield is selected rather than on the basis of irrigation amount.

Therefore where there is perfect forecast knowledge, irrigation requirements differentiate according to *n* number of years, with yield maximised according to the choice of 4 irrigation scheduling practices. Using a Fixed strategy there is 1 scheduling practice and 1 irrigation requirement, and using the SOI Forecast system there are 5 scheduling practice and irrigation requirement combinations. These three decision structures are conceptualised in Figure 5.1.

Figure 5.1 Conceptual diagram of how the 3 decision-support systems are defined for the “Fixed”, “Forecast” using 5 SOI Phases and “Perfect knowledge”.



For a forecast system to be useful, irrigation variability must differentiate significantly according to the 5 SOI Phases. This can be visually represented by the construction of cumulative probability distribution functions (CDF; Fig. 5.2). If there is little difference between the distributions then this suggests a Fixed strategy is adequate 100 % of the time. Perfect knowledge provides an indication of the improvement that can be made within a forecast system.

The irrigation requirements and DM potential for each of the strategies are presented as the 100 % irrigation requirement and 20 % yield minimum, for comparison. The yield minimum was calculated as the 20th percentile for total pasture grown over the period November to April. The 20th percentile was chosen to reflect a risk averse farmer profile which represents the minimum expectation 80 out of 100 years if 100 % of the irrigation requirement was available. Total yield for the irrigation season is also presented as box-plots, to demonstrate the total risk according to the spread of yields and median potential.

5.2.3 Forecast skill and user value

The statistical skill of the SOI Phase Forecast system, to reliably predict the irrigation requirements for maximising DM yield, was assessed using two non-parametric tests and confidence intervals. The Kruskal-Wallis (KW) test (Stone & Auliciems 1992) was used to compare differences in central value as indicated by the median, and the Kolmogorov-Smirnov (KS) test (Conover 1971) to identify significant differences between two CDF's. The KS test therefore detects differences due to both spread and/or shape of distributions. Because there were more than two comparisons the *P*-values were adjusted for multiplicity using Hochberg's multiple comparison procedure (Westfall *et al.* 1999). As a way of accounting for randomness or uncertainty in climate variability, confidence intervals around the CDFs were constructed using a bootstrap method. The bootstrap proceeded as follows. The data were re-sampled with replacement to construct 1000 CDFs for each Phase. This was performed in SAS using proc surveyselect. The 2.5 and 97.5 percentiles of each point along the bootstrapped CDFs were then calculated using proc univariate.

The user value of the Forecast system was evaluated by comparing total irrigation requirements and DM produced over the 108 years between the Fixed and Forecast strategies. Water-savings and DM yield gains where the Forecast system was used, therefore provides evidence for user value, which is expressed by a gain in irrigation efficiency (DM yield/irrigation; t DM/ML), defined as the irrigation water use index (IWUI).

Additional value occurs through being able to make tactical decisions, for example around water-trading – where there is improved precision around the irrigation requirements the opportunity cost is increased (due to lower risk) in terms of being able to trade when the irrigation availability is greater than the forecasted requirement. An economic analysis has not been performed in the current study to examine improvements in tactical decision-making, and therefore for simplicity it is assumed that water cannot be carried over from year to year, nor capitalised on through water trading. Thus efficiency gains are compared according to the absolute irrigation requirements under the Fixed and Forecast strategies, as opposed to irrigation use, which may vary from year to year.

User value was tested under two irrigation allocation scenarios – 1) where the allocation was non-restricted to achieve the highest yields possible using the different irrigation practices i.e. yield is limited by the defines of the irrigation rule, and 2) where the allocation was 50 % (250 mm) of the maximum requirements observed under the yield-maximising Practice 1, which represents an irrigation availability constraint. Under the constraint scenario, irrigation is still scheduled according to the irrigation practice rule, however no more irrigation is applied once 250 mm has been reached, resulting in the potential for end-of-season water stress.

5.3 Results

5.3.1 Dry matter yield and irrigation requirements under the different scheduling strategies

The DM yield and irrigation output for each of the 4 practices over 108 years is summarised in Figures 5.2 and 5.3, respectively. Between the different scheduling practices, irrigation availability had a variable affect on yield outcomes. Where irrigation availability was non-limited (no-constraint scenario), the spread in yield around the median (50^{th} percentile) or the slope of the distribution for each practice was similar, with yield limited by the irrigation input under each of the irrigation rules i.e. the distributions had similar shapes but shifted along the *X*-axis (Fig. 5.2A). The 50 % surety yield was 15.2, 15.0, 14.1 and 13.3 t DM/ha for Practices 1, 2, 3 and 4 respectively. Similarly, the 20^{th} percentile yields across all Phases reflected the difference in application rates between practices, with the highest yields observed for Practices 1 and 2, which applied 20 mm and 16 mm respectively at an irrigation trigger point, followed by Practice 3 (12 mm application) and Practice 4 (10 mm application) (Table 5.1A).

Under the irrigation constraint scenario the slope of the distribution for Practice 1 decreased significantly (P<0.001), indicating an increase in the yield variability, compared to the other three Practices (Fig. 5.2B). This was reflected in the 20^{th} percentile yield values, with Practice 1 and to a lesser extent Practice 2 experiencing reductions in yield, as a result of running out of water before the end of the irrigation season (Table 5.1B). The median yield of Practices 1 and 2 decreased to 13.9 and 14.6 t DM/ha, respectively, resulting in a narrower yield range between practices (14.6-13.3 t DM/ha; Fig. 5.2B). Practices 3 and 4 achieved the same yield distribution under maximum water availability and the constraint scenario due to the irrigation requirement being close to or less than the 250 mm maximum availability (Table 5.1A), i.e. the irrigation rule remained the limiting factor of yield potential.

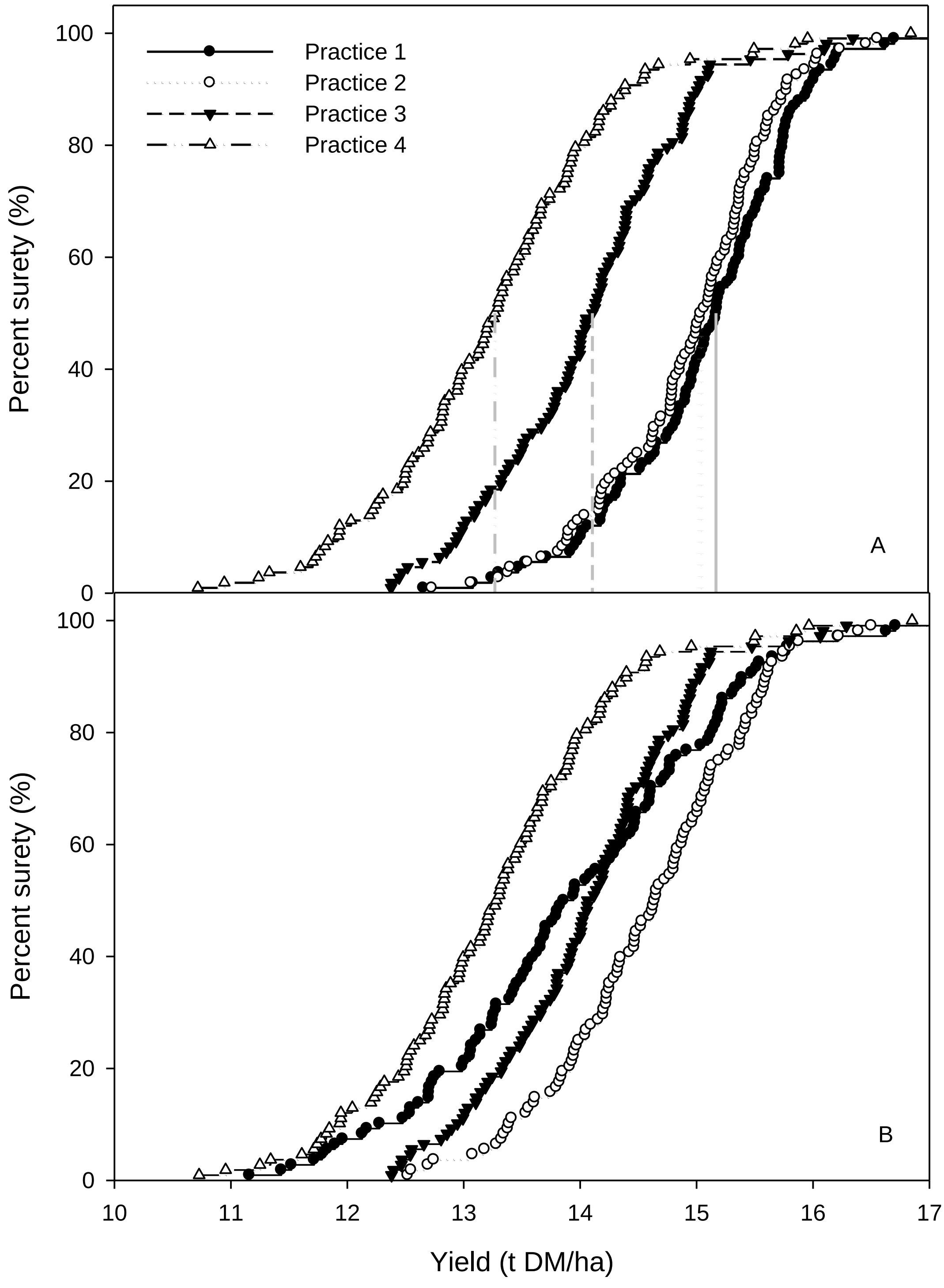


Figure 5.2 Cumulative distribution functions of dry matter yield (t DM/ha) for each of the 4 scheduling practices, under maximum water availability (A) and a 250 mm irrigation availability constraint (B). Reference lines indicate the median yield. Practices differ according to the application amount applied at a set rainfall deficit of 20 mm - Practice 1 (20 mm), Practice 2 (16 mm), Practice 3 (12 mm), and Practice 4 (10 mm). Percent surety indicates the likelihood of obtaining up to a given yield.

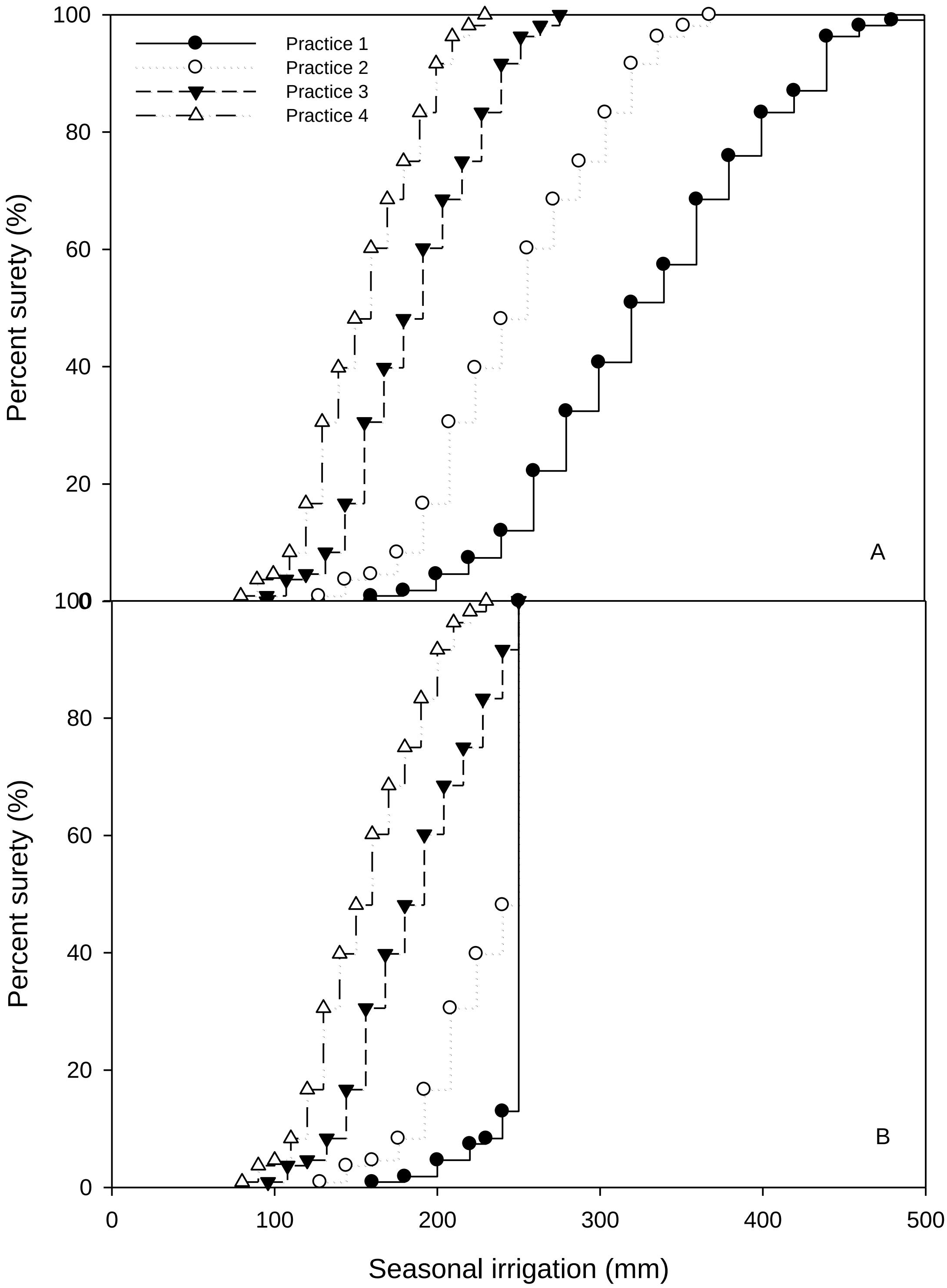


Figure 5.3 Cumulative distribution functions of seasonal irrigation applied (mm) for each of the 4 scheduling practices, under maximum water availability (A) and a 250 mm irrigation availability constraint (B). Practices differ according to the application amount applied at a set rainfall deficit of 20 mm - Practice 1 (20 mm), Practice 2 (16 mm), Practice 3 (12 mm), and Practice 4 (10 mm). Percent surety indicates the likelihood of requiring at least a given amount of irrigation.

Table 5.1 The maximum irrigation requirement (mm) and 20th percentile seasonal (November-April) dry matter yield (t DM/ha) for the four irrigation scheduling practices (1-4), stratified according to the Southern Oscillation Index (SOI) Phase (1-5) under two water availability scenarios – maximum availability (A) and a 250 mm irrigation constraint (B). Values in bold indicate the optimised practice according to the frequency of observations in each SOI Phase.

A.	**SOI Phase**				
Irrigation:	1	2	3	4	5
Practice					
1	460	440	500	380	480
2	**352**	320	**368**	288	352
3	264	**240**	276	**216**	**264**
4	220	200	230	130	220
Yield:					
Practice					
1	14.53	14.44	14.21	13.93	14.86
2	**14.67**	14.35	**14.11**	13.86	14.79
3	13.47	**13.54**	13.17	**13.10**	**12.34**
4	12.25	12.69	11.78	12.73	12.51

B.	**SOI Phase**				
Irrigation:	1	2	3	4	5
Practice					
1	250	250	250	250	250
2	250	250	250	250	250
3	**250**	**250**	**250**	**250**	**250**
4	220	200	230	130	220
Yield:					
Practice					
1	12.61	13.15	11.68	13.67	13.03
2	13.93	14.10	13.13	13.85	13.95
3	**12.48**	**13.57**	**13.17**	**13.10**	**13.34**
4	12.25	12.69	11.78	12.73	12.51

From the optimisation process, when water availability was non-limiting, Practice 3 was selected in 43 % of years, followed by Practice 2 (35 %) and Practice 4 (22 %) (Table 5.2A "All years"). Similarly, when water availability was capped to 250 mm, Practice 3 was observed the majority of the time (61%), followed by Practice 4 (28 %) and Practice 2 (11%) (Table 5.2B "All years"). The Fixed strategy practice under both irrigation allocation scenarios was therefore Practice 3, requiring 276 mm and 250 mm of irrigation seasonally to meet demand in 100 % of years under both scenarios, respectively (Figure 5.3).

Table 5.2 Number of times an irrigation scheduling practice achieved a yield maximum with the least amount of water within each Southern Oscillation Index Phase and in all years, under the no-constraint scenario (A) and when irrigation availability is capped to 250 mm (B), expressed as a percentage frequency (%). Practice 1 was observed 0 % in both water-allocation scenarios. The number of years in each Phase is given by *n*.

A						
Practice	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**All years**
2	41	30	50	31	33	35
3	41	47	20	47	46	43
4	18	23	30	23	21	22
n	22	30	10	13	33	108

B						
Practice	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**	**All years**
2	9	6	0	23	15	11
3	64	63	60	54	61	61
4	27	30	40	23	24	28
n	22	30	10	13	33	108

5.3.2 *Forecast system*

The cumulative distribution of irrigation followed a common pattern between practices, of convergence between Phases at the lower end (<250 mm) of irrigation requirement, with increasing differentiation as irrigation increased (Fig. 5.4A).

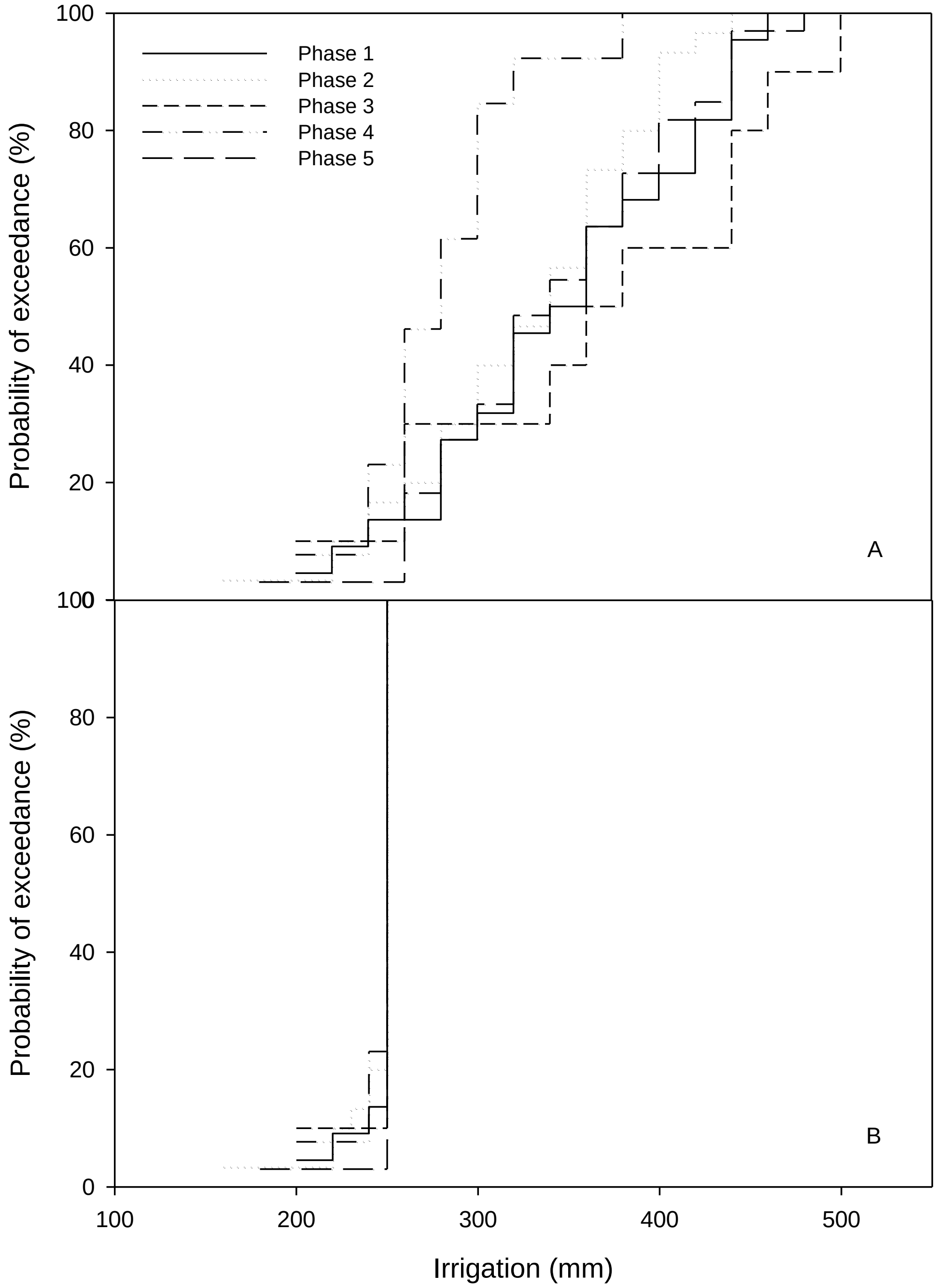


Figure 5.4 Cumulate distribution functions of irrigation requirements (mm) for Practice 1 stratified according to the 5 Southern Oscillation Index Phases when water is non-limiting (A) and cannot exceed 250 mm (B). Probability of exceedance indicates the likelihood of requiring above a given level of irrigation.

This resulted in differentiation in the maximum (100%) irrigation requirement between Phases for each practice (Table 5.1A), which was aligned with the minimum rainfall experienced in each Phase (Fig. 5.5), and provided opportunity for optimisation of the scheduling practice and irrigation amount between Phases.

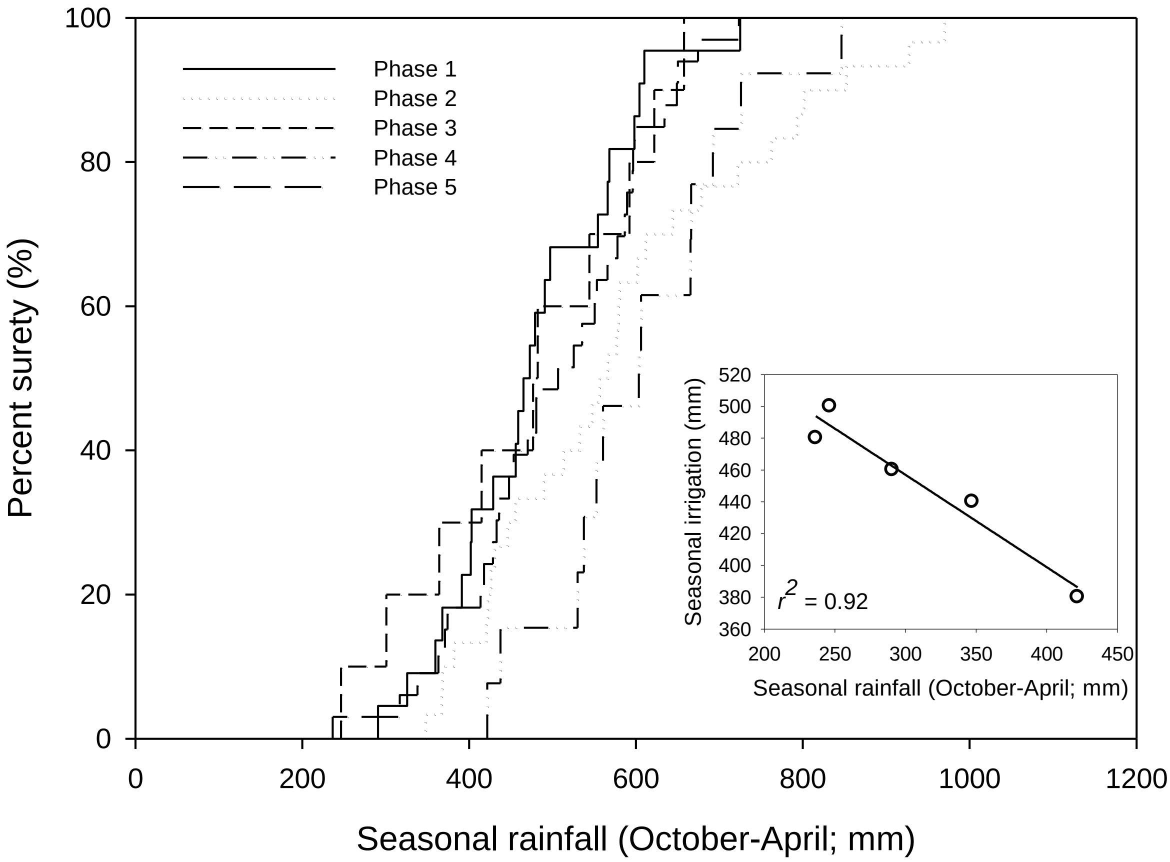


Figure 5.5 Cumulative distribution functions of seasonal rainfall (October-April) (mm) for Elliott, stratified according to the 5 Southern Oscillation Index Phases. Inset shows the regression between the minimum seasonal rainfall for each Phase against the maximum irrigation requirements in each Phase from Figure 5.3, with the adjusted coefficient of determination (r^2) provided.

Accordingly, the Forecast system predicted Practice 2 in Phase 3, requiring 368 mm of irrigation to meet the demand 100 % of the time, and also in Phase 1, requiring 352 mm. Practice 3 was similarly observed 41 % of the time in Phase 1 (Table 5.2A), but achieved a lower total yield (Table 5.1A). For Phases 2, 4 and 5, Practice 3 was the most frequently observed practice (Table 5.2A), requiring 240 mm, 216 mm and 264 mm to meet demand during each of the respective Phases (Table 5.1A).

When irrigation availability was limited to 250 mm, Practice 3 was the most frequently observed practice in all Phases (Table 5.2B). Due to convergence at the lower end of the irrigation CDFs, most practices applied the maximum allocation under the 250 mm constraint scenario (Table 5.1B), which was similar to that observed between Phases (Fig. 5.4B). Under the constraint scenario, the scheduling practice and irrigation requirements were the same for both the Forecast and Fixed strategies (Table 5.1B).

5.3.3 Forecast statistical skill

Statistical forecast skill for predicting irrigation requirements was assessed for Practice 1 using both non-parametric tests and confidence intervals. A significant difference between medians of Phases was detected using KW test, however when assessed according to KS test, even though Phase 4 was found to be significantly (P<0.05) different from Phases 1, 2 and 5 based on the un-adjusted P-values, when adjusted for multiplicity there was no significant difference between Phases (Table 5.3). This was consistent with the considerable overlap observed between the 95 % confidence limits, especially between Phases 1, 2 and 5 (Fig. 5.6).

Table 5.3 Raw and Hochberg adjusted *P*-values from comparing cumulative distributions of irrigation requirements of Practice 1 between the 5 Southern Oscillation Index Phases, using multi-sample Kolmogorov-Smirnov test. The Kruskal-Wallis (KW) test for divergence in medians between the distributions is also provided.

Phase	Raw *P*-value	Hochberg adjusted *P*-value
1+2	0.6539	0.9984
1+3	0.8990	0.9984
1+4	0.0210	0.1891
1+5	0.9984	0.9984
2+3	0.2656	0.9984
2+4	0.0457	0.3199
2+5	0.9320	0.9984
3+4	0.0248	0.1987
3+5	0.7305	0.9984
4+5	0.0148	0.1482
KW test	*P*-value = 0.0307	

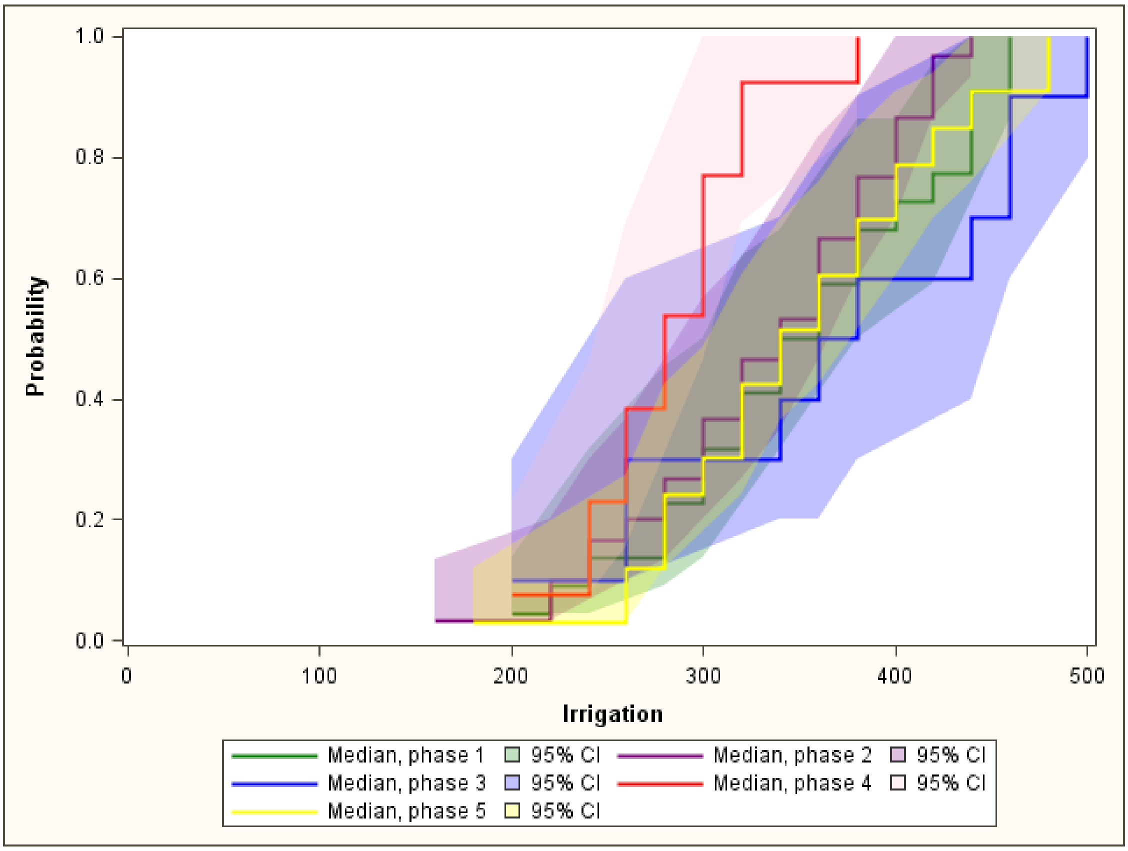


Figure 5.6 Cumulative distribution functions of irrigation requirements (mm) for Practice 1, stratified according to the 5 Southern Oscillation Index Phases when water is non-limiting. Confidence limits (95 %) are indicated by the shaded areas of each respective Phase.

5.3.4 User value

User value was assessed by comparing the total DM yield and irrigation applications over the 108 year run, and the consequent irrigation efficiency (IWUI) between the different decision-support systems. The potential of perfect knowledge was demonstrated with the greatest DM production and the least irrigation requirements under both irrigation availability scenarios, compared to the other decision-support systems (Table 5.4).

The benefits of the Forecast system were observed at two levels – 1) through water-savings from optimising the irrigation requirement in each Phase, where the Practice remained constant ("Fixed-phase"; Table 5.4A) and through DM gains and reduced yield variability from optimising the practice in each Phase ("Flexi-phase"; Table 5.4A, Fig. 5.7).

Table 5.4 User-value table comparing 4 decision-support systems according to the total dry matter yield (t DM/ha) and irrigation applied (mm) in each SOI Phase and over the 108 years ("Total"), under the maximum water availability (A) and 250 mm irrigation allocation constraint (B) scenarios.

A. Maximum water availability scenario

		SOI Phase					
	Decision-support system	**1**	**2**	**3**	**4**	**5**	**All years total**
Dry matter yield:	Perfect	320	437	145	185	481	1568
	Fixed	308	427	141	181	465	1522
	Fixed-phase	308	427	141	181	465	1522
	Flexi-phase	330	427	148	181	465	1551
Irrigation applied:	Perfect	4876	6024	2454	2240	6988	22582
	Fixed	6072	8280	2760	3588	9108	29808
	Fixed-phase	5808	7200	2760	2808	8712	27288
	Flexi-phase	7744	7200	3680	2808	8712	30144

B. 250 mm irrigation allocation constraint

		SOI Phase					
	Decision-support system	**1**	**2**	**3**	**4**	**5**	**All years total**
Dry matter yield:	Perfect	308	426	134	183	479	1531
	Fixed	309	429	136	181	467	1522
	Fixed-phase	309	429	136	181	467	1522
	Flexi-phase	309	429	136	181	467	1522
Irrigation:	Perfect	4210	5396	1954	2150	6308	20018
	Fixed	5500	7500	2500	3250	8250	27000
	Fixed-phase	5500	7500	2500	3250	8250	27000
	Flexi-phase	5500	7500	2500	3250	8250	27000

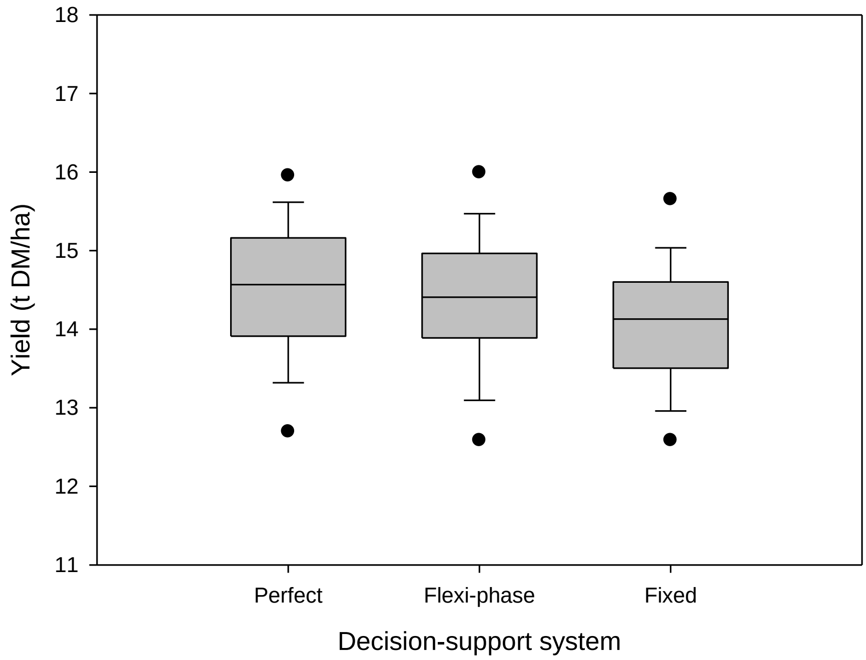


Figure 5.7 Box-plot of the distribution of seasonal dry mater yield (t DM/ha) for each of the three decision-support systems where water availability is non-limiting. Fifty percent of the data are contained in the box, with the middle line indicating the data median. The upper and lower edges of the box represent the 25th and 75th percentiles respectively, and the whiskers the 10th and 90th percentiles. The 5th and 95th outlying points are also given.

Saving water compared with improving DM outcomes, was effective in increasing the irrigation efficiency, with the Fixed-phase system achieving 5.6 t DM/ML compared with 5.1 t DM/ML where either a Flexi-phase or Fixed strategy was used (Table 5.5). Under the 250 mm constraint scenario there was no benefit from using a Forecast system (Table 5.4B), because the Forecast and Fixed strategies were the same (Table 5.2B).

Table 5.5 Irrigation water use index (IWUI), calculated as the ratio of total dry matter yield (t DM /ha) to total irrigation applied (mm) (t DM/ML) over the 108 years, achieved using the four decision-support systems when water availability is maximal ("No constraint") and cannot exceed 250 mm in a season ("250 mm constraint").

IWUI	No constraint	250 mm constraint
Perfect	6.9	7.6
Fixed	5.1	5.6
Fixed-phase	5.6	5.6
Flexi-phase	5.1	5.6

5.4 Discussion

5.4.1 The capacity of the SOI forecast system to predict irrigation requirements

Irrigation is applied to supplement rainfall where it is inadequate to meet water losses via evapotranspiration. In most temperate and semi-arid environments, a rainfall deficit (cumulative PET - rainfall) occurs annually, requiring application of irrigation water each year to maximise production of crops. In Figure 5.4A, the minimum requirement is illustrated by a convergence in irrigation between the 5 SOI Phases, with approximately 200 mm required in all years if pasture DM yield is to be maximised at Elliott, on the north-west coast of Tasmania. As the irrigation requirement increases, divergence between the distributions increase and saturate due to similar differences in minimum rainfall between the Phases (r^2 = 0.92, P<0.01) (Fig. 5.5).

However, not all rainfall contributes to the soil water pool within the root-zone for plant uptake, with losses occurring through evaporation, runoff and deep drainage. These losses vary depending on the soil water deficit at the time of a rainfall event and therefore also on the irrigation scheduling practice, with regards to how much water is applied at an irrigation trigger point (Rawnsley *et al.* 2009). Furthermore, the relative impact of differences in seasonal rainfall on irrigation requirements is dependent on evaporative demand. This is demonstrated by an increase in the variation accounted for by the regression between irrigation requirements and the ratio between rainfall to ET (r^2=0.79, P<0.001; data not shown), compared with where irrigation is simply regressed with rainfall received across a similar period (October-April) (r^2=0.59, P<0.001; data not shown). Therefore the strength of the association between the SOI and rainfall, which for some areas of Australia is strong (Goddard *et al.* 2001; Risbey *et al.* 2009), is not necessarily an indication of the capacity to predict irrigation needs.

The statistical skill of the Forecast system assessed using KW test was significant (P<0.05), supporting evidence for differences in the cumulative distribution functions for irrigation among the 5 SOI Phases (Fig. 5.4A). Phase 4 was identified as being significantly different from Phases 1, 2 and 5, however when adjusted for multiplicity at the 95 % confidence level, these differences were not significant as a group (Table 5.3). Presenting confidence bands around each probability distribution is an additional means to evaluate the precision around the median and shape of the distributions and hence the uncertainty in climate variability or serial (intra-seasonal) dependency. Figure 5.6 shows that there was substantial overlap between the confidence bands, especially between Phases 1, 2 and 5. However in terms of the expectations related to climate uncertainty, this method to evaluate forecast skill is relatively new (Dunn 2001; Maia & Meinke 2010) and therefore comment cannot be made as to how results found in the current study compare to similar forecast simulations in different regions of Australia.

5.4.2 Crop simulation modelling

Whilst the SOI forecast system predicts irrigation requirements, for tactical decision making around stock levels and the need for additional brought in feed, an understanding of the yield outcome from an irrigation requirement is also required. Dry matter production can be predicted on the basis that an irrigation requirement is the cumulative use of water achieved under a scheduling practice (Fig. 5.3A) which can be translated into DM returns through the use of a biophysical crop model (Fig. 5.2A). The capacity of crop models to integrate soil and atmospheric dynamics through the effect on DM yield provide a time and cost-efficient alternative to experimentation on the physical system for testing alternative management strategies and resource issues (Meinke *et al.* 2001).

Representing the effects of rainfall through biological indices such as plant growth days or yield often improves the forecast skill compared with where only rainfall is used (Keogh *et al.* 2004a; McIntosh *et al.* 2005; Meinke & Stone 2005). Furthermore, considering that DM yield is a key driver in dairy profitability (Armstrong *et al.* 2010; Chapman *et al.* 2008), forecast information based on production indicators rather than crude rainfall probabilities may be more relevant and therefore easier to integrate into farmers' responses to seasonal climate risk (Ash *et al.* 2007). In the current study, pasture DM consequences are incorporated in the decision-support system by optimising the choice of the irrigation scheduling practice according to the practice that maximises yield for the least amount of irrigation.

Production risk associated with using a particular scheduling practice in a given Phase is also provided by the 20th percentile yield minimum; however this could be adjusted according to the risk level of the farmer and enterprise. Production risk from using the Forecast system occurs because whilst using the maximum observed irrigation amount in a Phase for the selected practice meets the requirement in 100 % of years, yield will not necessarily be the maximum achievable for that season had another scheduling practice that uses more water been implemented. This can be understood by the different yield distributions of each practice in Figure 5.2A. Thus information provided by the Forecast system in combination with simulation modelling, includes an irrigation amount (Table 5.1), a scheduling practice (Table 5.2), and a potential DM yield (Table 5.1).

5.4.3 User value

The value of forecast information is often assessed in terms of changes to gross margins, farm profit and/or utility (Abawi *et al.* 1995; Hammer *et al.* 1996; Ritchie *et al.* 2004). Such an economic analysis has not been performed in the current study. However gains in DM yield and savings to irrigation amount have been used to assess the user value of the Forecast system compared with where a best-bet Fixed strategy is followed each year. This has been assessed under two water availability scenarios – where the water allocation is non-limiting, and where cumulative water use cannot exceed 250 mm.

Under maximum water availability, the greatest improvement to irrigation efficiency was observed in the Fixed-phase decision-support system, where the practice was fixed (Practice 3) but the irrigation requirements differentiated according to the SOI Phases (Table 5.4A). Compared to a Fixed strategy where Practice 3 was used, requiring 276 mm annually, the Fixed-phase strategy reduced irrigation requirements by 8.5 % (Table 5.4A), resulting in an 0.5 t DM/ha increase in irrigation efficiency (Table 5.5). However, in situations where maximising yield is a higher priority over irrigation use, for example when irrigation availability is not restricted or is cost viable, then the Flexi-phase forecast system is recommended (Fig. 5.7), due to the gains in DM yield obtained from using Practice 2 following Phases 1 and 2 in October (Table 5.1A). That is, in using the Fixed-phase system, improved irrigation efficiency was achieved at the cost of DM yield. However the value of this reduction is likely to vary depending on whether feed or irrigation is more limiting (Armstrong 2004; Ho *et al.* 2007). Interestingly, Practice 1, which is the current industry recommended practice applied at Elliott, was not required to maximise DM yield, suggesting that rainfall utilisation was increased where alternative practices were selected for during the optimisation process (Table 5.2A).

As the irrigation allocation decreases and gets closer to the minimum irrigation requirements of the environment, less differentiation in water requirements (and therefore potential savings) from a Forecast system is expected due to convergence between the Phase distributions (Fig. 5.4). This was the case under a 250 mm allocation constraint, with Practices 1-3 using the full allocation in each Phase (Fig. 5.3B). As such, the Forecast strategies were the same as the Fixed strategy (Table 5.4B), negating the need for pre-season information under constraint conditions, and limiting the opportunity to improve irrigation efficiency (Table 5.5). Furthermore, as water availability becomes limiting to growth, the yield distributions converge between practices (Figure 5.2B). Compared with Practices 3 and 4 where there was no change between allocation scenarios, Practice 1 observed a significant change in the median and shape of the distribution ($P < 0.001$), depicting increased variability in DM yield (Figure 5.2). The different effects on DM yield reflect the trade-off between short-term stress and end-of-season stress where water has run out before the end of the season. In the case of Practice 1 there was increased risk associated with maintaining short-interval schedules that refill the soil profile to field capacity, over ensuring longer-term water availability through practising a deficit irrigation strategy (Practices 2-4). This is the basis for supplementary irrigation to stabilise yields in Mediterranean climates (Oweis *et al.* 1998) and can also be applied to the rationale of irrigating over a larger area at a lower irrigation application rate compared with maximising water use over a smaller area to increase the marginal response of irrigation water (Kirda 2002; Rawnsley *et al.* 2009).

5.4.4 Advantages and limitations of a forecast system

The capacity of a forecast system to achieve improved irrigation efficiency is through better matching of irrigation requirements with seasonal demand according to the choice of the irrigation scheduling practice, and through pre-season knowledge of irrigation requirements and DM yield potential for optimising resources for the best returns. In this regard, forecast knowledge provides a means to quantify the level of dryness of the up-coming season in terms of potential impacts to resources, for improved drought preparedness (White 2000). Currently however, long-term seasonal outlooks are used to a lesser degree than short-term weather forecasts due mainly to the perceived inaccuracy of longer term predictions and the difficulty in integrating probability measures into management decisions (Ash *et al.* 2007; Austen *et al.* 2002; Cobon *et al.* 2008).

The results presented in the current study are limited by the assumptions of the biophysical model and serial dependency of the distributions on the historical climate dataset used for the analysis. Despite the fact that DairyMod has been evaluated in the current study environment under similar irrigation and management practices (Rawnsley *et al.* 2009), the model represents deterministic outcomes and therefore there are likely to be additional risks that have not been accounted for due to inherent farm system and environmental variability. Thus whilst the analysis conducted in the current study is useful and indicative of the information that can be obtained from using a forecast process, further evaluation of pre-season knowledge taking into account model and climate uncertainty is required to gain a better indication of the potential economic benefits before adoption by irrigators is likely. This may also provide a truer benchmark of forecast capacity compared with where fixed strategies are practiced and conversely how far away the forecast system is from achieving perfect knowledge outcomes.

In a survey of 174 regulated irrigators in the northern Murray-Darling Basin, it was found that only 29 % of farmers applied the SOI to property decisions (Keogh *et al.* 2004b), with the majority (69 %) using it to help determine the choice of crop and area, rate of fertiliser application, harvesting, sowing date and stock rates, and 20 % using the SOI directly for water availability and management decisions (Keogh *et al.* 2004a). In the same study however, almost 60 % of farmers that participated indicated that a tool/information system for water and climate-related decisions would be useful (Keogh *et al.* 2004a), suggesting that there is demand for seasonal forecast information but not necessarily in the form currently available to farmers. The use of participatory approaches in the development of SOI forecast systems has been identified as an important means of ensuring forecast relevance and information transfer for effective uptake (Everingham *et al.* 2008; George *et al.* 2007; Meinke & Stone 2005), and is therefore suggested as an additional priority for future development of the forecast system for irrigation management in pastoral systems.

5.5 Conclusion

The value of pre-season information on irrigation requirements for optimising the irrigation scheduling practice has been tested as a means to improve irrigation efficiency and DM production outcomes under two irrigation availability scenarios. The SOI Phase system has been used for this purpose based on the strong links between ENSO activity and rainfall variability that has been demonstrated for parts of Australia. Seasonal forecasting was successful in maximising DM production for the least irrigation input when irrigation availability was non-limiting, but when the irrigation allocation was reduced by 50 %, convergence between SOI Phases meant that the Fixed and Forecast strategies were the same. An economic assessment taking into account other management decisions that may be improved from seasonal irrigation forecasts, such as irrigated area and water-trading, is required to obtain a full sense of the forecast system potential.

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Chapter 7: General discussion

7.1 Summary

The high dependence on irrigation water in pastoral systems derives from the linear relationship between transpiration and biomass (Steduto *et al.* 2007) and the general sensitivity of forage grasses to water stress, particularly the process of leaf elongation (Norris & Thomas 1982a). Therefore anywhere where a summer rainfall deficit occurs, there is a requirement for irrigation water if pasture DM is to be maximised. There has been much effort to measure the irrigation requirements of pasture and in doing so benchmark WUE across dairying regions in Australia (e.g. Armstrong *et al.* 2000; Bethune & Wang 2004; Greenwood *et al.* 2009; Khan *et al.* 2010a). There are also general rules of thumb that have been developed based on soil water holding capacity and rooting depth to direct irrigation scheduling to maximise DM yield, which form the basis of irrigation scheduling handbooks published by state agricultural departments (e.g. "Wise Watering Irrigation Management", Tasmanian Department of Primary Industries, Parks, Water and Environment). However, the relative abundance of water for irrigation, particularly in Tasmania, has meant that there has not been the necessity to improve irrigation efficiency or for farmers to seek information, and as a result water has tended to be applied in excess. In view of recent droughts and growing environmental awareness, quantifying water use and understanding plant demand has become an increasing imperative, and in particular, the options available for maximising DM returns when irrigation availability is below crop water requirements (Armstrong 2004; Ho *et al.* 2007).

In this thesis, I investigated the potential of deficit irrigation to improve the DM returns of pasture, in particular *Lolium perenne* L. (perennial ryegrass) under water-limited conditions. The capacity to improve irrigation efficiency was examined according to the regulation of water use at the leaf-level, and through improving utilisation of rainfall at the field-level. Both agronomic and physiological measures of production and water use were measured within field and glasshouse studies under a range of deficit irrigation practices and contrasting scheduling technologies, including a rainfall deficit water balance approach and direct measures of soil moisture using gypsum Watermark^{TM} sensors. The influence of climate variability on deficit irrigation outcomes was addressed with the use of seasonal climate forecasts for predicting irrigation requirements and through forage selection, which involved determining the variability in water use traits and their relevance to drought resistance between two commercially important forage species, *Festuca arundinacea* Schreb. and *Lolium multiflorum* Lam.

The results of this work have confirmed that there is the potential to improve irrigation efficiency through the use of deficit irrigation practices, without negatively impacting on either herbage DM yield or nutritive value (Chapter 3). Irrigation savings are likely to be driven largely by increased rainfall utilisation on the basis that midday WUE of well-watered plants was already quite high in the field (Chapter 4). As a result, where rainfall utilisation was suspected to have been similar between well-watered and deficit irrigation practices, DM yield declined with reduced irrigation inputs. That said, results under glasshouse conditions indicated the potential to significantly augment WUE without penalty to yield, through regulating soil water availability on a diurnal basis (Chapter 2). Therefore whilst improved leaf-level WUE was not demonstrated in the field, under alternative scheduling strategies and technologies there is the potential for improved plant water use to be achieved.

The three management strategies tested to minimise the yield penalty associated with deficit irrigation were all successful at various levels of the production system – scheduling irrigation according to soil moisture sensors improved integrated WUE over time by helping to maintain plants at the desired soil water deficit and regulating the amplitude in soil water availability experienced (Chapter 4); seasonal forecasting showed the potential for maximising DM yield for the least irrigation input, but when the irrigation allocation was reduced by 50 %, there were no benefits from using the system (Chapter 5); and variability in water use traits between grass species indicated that in not all cases does water conservation result in a yield penalty, providing opportunity to select for certain traits depending on the environment and irrigation strategy (Chapter 6).

In the following sections I will review the opportunities and limitations to improve irrigation efficiency according to how aspects of agronomy and physiology detailed in the 5 experimental chapters contributed to achieving improvements in leaf- or field-level WUE. In doing so, I will discuss the key findings with relevance to irrigation management in pastoral systems. I will also outline the limitations associated with this research and highlight important new questions that have emerged during the study.

7.1.1 Leaf-level improvements in WUE

In the glasshouse experiment detailed in Chapter 2, an examination of the water transport system and stomatal regulation indicated that ryegrass has the capacity to transport more water than is required to maintain maximal *A* rates, and furthermore, water use could be reduced without permanent hydraulic damage. Accordingly, improved WUE was the result of three main factors: the non-linear relationship between *A* and *gs*; the capacity to respond to water inputs for much of the leaf functional water potential range; and maximal utilisation of hydraulic investment with stomata closing after 50 % loss of hydraulic conductivity. The apparent resilience of the grass plant with regards to diurnal exposure and recovery from hydraulic dysfunction was a unique finding as in most woody plants where the majority of hydraulic investigation has occurred, recovery of gas exchange and hydraulic function tends to be slow (Brodribb & Cochard 2009). Under soil drying the plant was still at risk of drought-induced dieback, which coincided with ~80 % loss of K_{leaf} and *gs* functionality at a Ψ_{PD} of -1.5 MPa. However, dieback was avoided in the sustained drought treatment by manipulating diurnal water availability such that water use was restricted during daylight hours, and high leaf water potential (Ψ_{leaf}) at night ensured utilisation of carbon gain for growth with minimal loss of water via transpiration.

The results as they apply to irrigation management suggest that:

1) soil water deficits causing dieback should be avoided as they reduce WUE and senescent herbage has a reduced nutritive value;
2) soil water deficits must persist to increase WUE through eliciting stomatal closure; but
3) in order to utilise carbon gain for growth, leaves must be well-hydrated.

Visual monitoring of pastures and calibration of irrigation trigger points with the onset of pasture senescence could be used to define the maximum soil water deficit at which WUE is maximised. However, manipulating diurnal soil water availability in the field to achieve both high Ψ_{leaf} for growth overnight and reduced midday Ψ_{leaf} to enhance WUE may be more difficult to achieve on a diurnal basis.

Using soil moisture sensors to schedule irrigation events in the field, improvements to WUE were achieved over time by maintaining plants at the desired soil water deficit and regulating the amplitude in soil water availability experienced. This resulted overall in an increase in irrigation efficiency of 0.24 t DM/ML for both well-watered and deficit irrigation practices, equating to a water saving of 20-33 % compared to where irrigation was scheduled according to a rainfall deficit, which uses estimated ET from meteorological data or an evaporative pan. However, in terms of instantaneous midday WUE, even well-watered plants were regulating at a relatively high WUE, compared to well-watered glasshouse plants in Chapter 2.

The disparity between well-watered glasshouse (Chapter 2) and field grown plants (Chapter 4) suggests that evaporative demand was greater in the field, and therefore despite soil water being readily available to maintain optimal leaf elongation rates, diurnal decline in K_{leaf} may be occurring at much higher Ψ_{soil}. Therefore increasing the soil water deficit further may reduce the capacity to utilise carbon in growth by preventing plants from re-hydrating completely overnight and/or through increasing the period of time stomata are closed during the day, therefore limiting carbon assimilation. This hypothesis requires further testing, however greater sensitivity of K_{leaf} to declines under field conditions would support the results reported in Chapter 4 of the linear reduction in DM yield with irrigation inputs and observations reported elsewhere (Merot *et al.* 2008; Smeal *et al.* 2005). Importantly, the saturating curve between yield and transpiration which is the basis for the use of deficit irrigation in cereal crops (Farre & Faci 2006; Kang *et al.* 2002), is not applicable to herbaceous vegetative crops. Furthermore, the curvilinear relationship between WUE and Ψ_{leaf} reported in Chapter 4 provides further evidence that water conservation will be largely at the detriment of DM yield.

Drought resistance is commonly proposed as a method to improve WUE, however within the grass literature the definition of advantage in selecting for higher WUE has not always referred to improved DM yield. Furthermore, unlike in Mediterranean environments with persistent periods of dry weather, temperate environments are characterised by intermittent rainfall. Therefore drought resistance should also not be to the limitation of well-watered production potential. In Chapter 6, a further examination of the water transport system was instructive in defining dehydration tolerance and avoidance according to the water use traits *P50* and stomatal regulation respectively, and understanding the trade-offs in water use and DM yield according to maximum hydraulic conductivity and the hydraulic safety margin. This is the first methodological approach for forage grasses to examine the consequences of water shortage and production potential under well-watered conditions.

Variability between grass species pertained to dehydration avoidance characteristics, namely stomatal regulation rather than dehydration tolerance conferred by *P50*. Stomatal closure in *L. multiflorum* occurred at less negative Ψ_{leaf} than *F. arundinacea* cultivars, resulting in improved WUE under soil water deficit conditions compared to the well-watered situation. Dry matter returns were similar to *F. arundinacea* through higher maximal hydraulic conductivity and stomatal conductance, allowing for higher rates of carbon gain when Ψ_{leaf} was favourable. Whilst *F. arundinacea* consequently used more water than *L. multiflorum* under the water deficit condition, the concomitant increase in carbon gain from closing stomata at a lower Ψ_{leaf} meant that overall WUE and DM yield were similar between the two species. That is, the two hydraulic strategies were balanced under the sustained soil water-deficit conditions tested. However when plants were subject to soil drying to -200 KPa, the reduced hydraulic safety of *F. arundinacea* exposed leaves to increased proportions of leaf dieback.

The importance of these results relates to the specialisation of plant function for different spatial and temporal variation in soil moisture. Therefore for irrigation management, species variation provides the opportunity to matching the species grown to the environmental conditions and water availability scenario, so that DM yield is maximised and hence so too is irrigation efficiency. For example, given that *F. arundinacea* species tend to have larger root systems (Durand *et al.* 2007; Garwood & Sinclair 1979), prolonged stomatal opening of *F. arundinacea* may allow for continued utilisation of stored water deeper in the soil profile, and therefore larger infrequent irrigation scheduling strategies may maximise the plant's characteristics. In comparison, where deeper water is not available, the conservative stomatal function of *L. multiflorum* may be more advantageous, and similarly respond better to short-interval, smaller irrigation applications.

7.1.2 Field-level improvements in irrigation efficiency

A range of irrigation practices were tested in Chapter 3, that were designed to expose plants to different stress intensities and periods of soil water deficit to investigate whether there was a trade-off in DM yield from increasing the soil water deficit to improve the probability of capturing rainfall. The greatest limitation of this work was that soil water changes were not measured and therefore it is not known whether DM yield similarities between treatments were due to increased WUE in the deficit irrigated treatments, or because treatments used similar amounts of total water i.e. rainfall utilisation differed. However the fact that total DM yield didn't vary significantly between deficit irrigated and well-watered treatments except for one strategy, suggests the latter reasoning. Furthermore the average leaf elongation rate, tiller number, tiller DW and root length density did not differ between irrigated treatments, and not surprisingly therefore, neither did the nutritive value of the herbage. As a result, irrigation efficiency differed, with the greatest water savings observed where a soil water deficit of 60 mm was practiced.

In the subsequent irrigation season, a similar 60 mm soil water deficit was scheduled according to both a rainfall deficit and an equivalent Ψ_{soil}. Soil water sensors buried at 0.3 m, where the majority of the root-zone ended, were used to monitor changes in water availability. Sensors in both well-watered and deficit irrigated practices rarely reached higher than -10 KPa, which suggests saturation of the root-zone. Therefore in this case, rainfall utilisation was considered to be similar, resulting in a reduction in total water used in the deficit irrigated plots and a decline in DM yield.

The implication is that where rainfall utilisation is the main driver of differences in irrigation efficiency, seasonal variability in rainfall distribution patterns may represent a risk to practising deficit irrigation. In Chapter 5, seasonal crop forecasting was proposed as a way to improve the precision of scheduling choice according to the maximum amount of irrigation required in each of the 5 SOI Phases. Crop simulation modelling was used to identify the scheduling practice that maximised DM yield for the least amount of water, and therefore, under perfect forecast knowledge rainfall utilisation was maximised each year.

For a forecast system to be useful, inter-annual variation in irrigation requirements must differentiate significantly according to the 5 SOI phases. Statistically and through visual assessment of confidence limits, the strength of the relationship between irrigation requirements and the SOI Phase system appeared poor, with differences in the distributions occurring by chance, and large overlap between 95 % confidence bands suggesting serial dependency of the cumulative distribution functions on the historical climate dataset used for the analysis, or in other words, climate uncertainty. However in terms of user value, the forecast system maximised DM yield over a fixed scheduling strategy when water was non-limiting, and increased WUE as a result of maximum irrigation requirements ranging between 216-276 mm in Practice 3, between SOI Phases.

Reflective of the annual rainfall deficit conditions occurring in this temperate environment, in the 108 year historical climate series analysed, a minimum irrigation requirement of ~200 mm/yr was consistent between phases. As a result, when the irrigation allocation was reduced by 50 %, both Fixed and Forecast strategies were the same, thus negating the need for a forecast system. However what was illustrated from the analysis, was the yield advantage from practising a deficit irrigation strategy over the industry practice of irrigating to field capacity and running out of water before the end of the season. This suggests that when water is limiting, DM returns can be increased through irrigating over a larger area at a lower irrigation application rate compared with maximising water use over a smaller area. Whilst seasonal forecasts provide intra-annual precision in irrigation allocation, within season scheduling of irrigation events with the use of soil water sensors is likely to be of greater benefit given the significant regression between DM yield and Ψ_{soil} at an irrigation trigger point, reported in Chapter 4.

7.2 Conclusion

This study has taken a holistic approach to irrigation management, integrating crop physiology, agronomy and simulation modelling to analyse the potential of deficit irrigation to improve irrigation efficiency in temperate pasture systems. This reflects the fact that water use is considered a chain of efficiencies in which the summation of parts provides a significant opportunity to increase WUE. Opportunities and limitations to improving WUE at both the leaf- and field-level have been identified. This thesis provides good evidence to suggest that deficit irrigation is a viable means to improve the irrigation efficiency of pastoral systems in temperate environments. Where rainfall utilisation can be increased, deficit irrigation can be practised with minimal penalty to DM yield. However where seasonal rainfall is minimal and irrigation availability is limiting, deficit irrigation may act to stabilise yields over a larger area to improve net DM returns. Management strategies such as seasonal climate forecasting, soil moisture monitoring and species choice can be considered options to manage the risks associated with seasonal variability and to improve the precision of within season irrigation allocation. An understanding of grass physiology has been integral to the interpretation of morphological observations in the field and for identifying the constraints on plant function with respect to the transport and exchange of water for carbon. Further cross-analysis of the links between plant physiology and agronomy will be imperative to finding novel and holistic solutions for managing crop production in water-limited environments.

7.3 Future research opportunities

There have been many aspects to this thesis including crop physiology, agronomy and simulation modelling and as a result there have also been many new and important questions that could not be investigated. Some areas for future research are therefore considered below:

- ***Determining the mechanism by which hydraulic conductivity declines and recovers diurnally***

The relevance of hydraulic dysfunction to the survival (recovery) of existing aerial biomass within the grass context was challenged in Chapter 2, where declines in Ψ_{leaf} capable of reducing K_{leaf} substantially did not have a significant effect on DM yield. This was a unique finding as in most woody plants where the majority of hydraulic investigation has occurred, recovery of gas exchange and hydraulic function from loss of K_{leaf} tends to be slow (Brodribb & Cochard 2009). The capacity for rapid recovery in grasses was hypothesised to be as a result of hydraulic dysfunction being driven by turgor loss or cell collapse rather than xylem cavitation (Blackman *et al.* 2010; Brodribb & Holbrook 2005), efficient root pressure (Tyree *et al.* 1986), and transient production in the phytohormone ABA to limit the rate of stomatal opening during recover of Ψ_{leaf} (Lovisolo *et al.* 2002). This however needs substantiating, but would have important bearing on the functional differences between herbaceous and woody plants from an evolutionary perspective, and provide further insight into the opportunities to manipulate the management of grasses for agricultural benefit.

- ***Identifying whether variation in osmotic adjustment (OA) in relation to the water transport limits of xylem equates to differences in hydraulic safety and therefore the relevance of OA as a trait for water-limited environments***

In Chapter 2 it was observed that OA in leaves shifted the turgor loss point beyond the point that 95 % loss of K_{leaf} occurred. Therefore as a drought resistance trait, the benefits are unlikely to be from improving gas exchange to maintain growth under water-limited conditions. It would be interesting to determine if there is a limit to OA in grasses and how this relates to the water transport system. In particular, where differences in OA exist between species, the environmental conditions under which selection has occurred should be explored, to understand under what circumstances OA is likely to be of benefit.

- ***The importance of the hydraulic buffering of A by Kleaf under high evaporative conditions and the implications for WUE***

Hydraulic redundancy provides a greater buffering capacity of Ψ_{leaf} and hence gas exchange to VPD (Maherali & DeLucia 2000; 2001). Under water-deficit conditions therefore, increased VPD would mean that the available water is used at a faster rate with no net benefit to carbon gain i.e. WUE is reduced. From an irrigation management perspective, this suggests that there is less opportunity in high VPD environments to achieve gains in WUE, and furthermore DM yield is likely to reduce to a greater degree than when under low VPD conditions with similar soil moisture. Understanding the effect of VPD on WUE is therefore important to the recommendation of deficit irrigation for different dairying regions in Australia.

- ***Determine how water transport traits are coordinated to influence carbon allocation between roots and shoots.***

The influence of roots on the carbon balance, under both well-watered and water-deficit conditions, was not able to be tested in Chapter 6 due to restrictions of the potting depth. However in the case of *F. arundinacea* for example, improved rooting may be an important moderator of the reduced hydraulic safety displayed by this species compared to *L. multiflorum*, and in this instance, provide a DM yield advantage under prolonged soil drying. Glasshouse experimentation with longer pots or field comparisons could be undertaken to investigate these relationships.

- ***Further characterise species within Poaceae according to P50, stomatal regulation and hydraulic conductivity to determine if the cross-over between drought resistance strategies or distribution of species along soil water gradients can be explained by similar changes in hydraulic strategies, for example whether variation in P50 exists or whether dormancy is a more efficient method of drought tolerance.***

My study demonstrated the capacity of water use traits to explain differences in WUE and DM production between cultivars within the *Festuca-Lolium* complex, and under water deficit conditions, provided a means to quantify relative drought resistance (Chapter 6). Because the water transport system integrates responses within the soil-plant-atmosphere continuum and accordingly the roots and shoots, it may have a greater advantage in identifying co-related traits where physiological parameters are analysed in isolation. Therefore further investigation with other species is warranted, including the potential to use anatomical traits as a selection tool for screening for drought tolerance.

- ***Quantify diurnal changes in hydraulic conductivity and WUE in the field***

Midday WUE according to instantaneous gas exchange of well-watered plants in the field was much higher than similar plants grown in the glasshouse (Chapter 4). As a result, there appeared to be less opportunity to augment WUE in the field than was suggested by the glasshouse results (Chapter 2). Midday WUE values however are likely to be indicative of the period of greatest stress in the day. Assessment of diurnal changes in WUE and K_{leaf} would therefore be useful to better understand the extent to which leaf level WUE can be increased in the field.

- ***Determine the contribution of rainfall utilisation to improvements in irrigation efficiency***

One of the major limitations of this work was the fact that rainfall utilisation was not explicitly measured. This would require a greater number of sensors to depth to determine if drainage was occurring past the root-zone (preferably volumetric sensors so that lab-derived retention curves are not required), or use of a lysimeter to accurately determine the soil water balance. Both of these options were not available to my study. Manual volumetric soil sampling was also not feasible. As rainfall utilisation may be the major driver of increased irrigation efficiency, quantification of this hypothesis is warranted and would indicate whether deficit irrigation is an option where seasonal rainfall is minimal.

- ***Trial deficit irrigation with different species under varying soil types and environments***

This study has been focused on perennial ryegrass within a temperate environment. Field testing was undertaken on a red ferrosol clay-dominated soil type and sandy-loam in the glasshouse experimentation, both of which have very different water-holding capacities and opportunity for root penetration under soil drying. Variability in species responses to soil water availability was documented in Chapter 6. Therefore further testing of root-soil interactions on water use and genotype by environment effects on the effectiveness of deficit irrigation would be useful for customising scheduling practices to ensure maximum returns on irrigation inputs. Furthermore, field experimentation was conducted over two seasons (although not the same experimental design each year), and in Chapter 3 was over a contracted period of the irrigation season. Multi-year studies would be beneficial to determine the effects of seasonal variability on the potential of deficit irrigation.

- ***Perform a feasibility test to determine the economic viability of using soil moisture sensors to variably irrigate paddocks and whether alternative more accurate sensors are worth the additional expense in terms of irrigation efficiency gains***

Watermark^{TM} sensors were used in Chapter 4 because they are reasonably priced and therefore multiple sensors could be purchased to capture spatial variability within the paddock. However they are not as precise as some of the more expensive technologies available. Irrigation savings of 20-33 % were observed from using the average of 9 sensors to schedule irrigation events over 3 experimental plots per treatment. Further testing is required to determine if practising precision irrigation would achieve additional efficiency gains and the definition of management zones for this purpose. Improved confidence around the predictability of the relationship between DM yield and Ψ_{soil} is required if Watermark^{TM} sensors are to be used to trigger scheduling events.

- ***Test the forecast system in different dairying regions and perform an economic analysis that evaluates the benefits of improved knowledge for making pre-season tactical decisions such as the trading of water***

Teleconnection between the SOI Phase forecast system and rainfall has been demonstrated to be strongest on the north-east coast of mainland Australia. Therefore it would be interesting to see if irrigation efficiency is further improved where the forecast system detailed in Chapter 5 was applied to regions with stronger inherent forecast skill. User-value was tested according to gains in DM yield and water savings. However an economic analysis may be more representative of farmer priorities.

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